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# **Design, Synthesis and Biological Evaluation of Fused naphthofuro[3,2-c]quinoline-6,7,12-triones and pyrano[3,2-c]quinolone-6,7,8,13-tetraones derivatives as ERK inhibitors with Efficacy in BRAF-mutant Melanoma**

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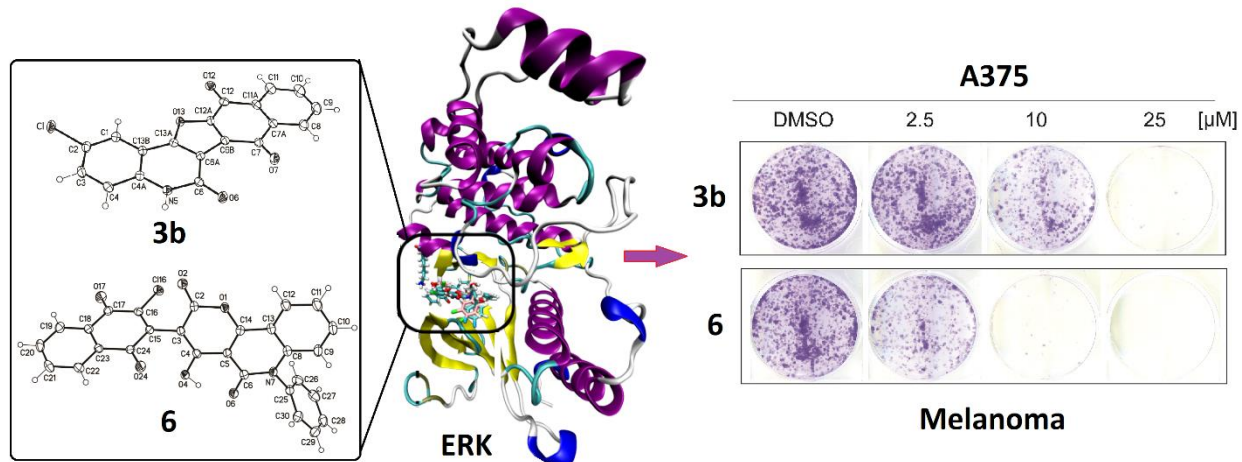
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## Graphical Abstract



## Highlights

- A group of naphthofuro[3,2-*c*]quinoline and pyrano[3,2-*c*]quinoline derivatives were synthesized.
- The compounds inhibited ERK in an ATP-competitive manner.
- **3b** and **6** exhibited pronounced cytotoxicity against the NCI-60 panel of human tumor cell lines.
- **3b** and **6** inhibited ERK in the A375 melanoma cell line, suppressed colony formation and induced apoptosis.
- Molecular modeling studies suggested the binding of the inhibitors within the ERK active site.

## Abstract

Approximately 60% of human cancers exhibit enhanced activity of ERK1 and ERK2, reflecting their multiple roles in tumor initiation and progression. Acquired drug resistance, especially mechanisms associated with the reactivation of the MAPK (RAF/MEK/ERK) pathway represent a major challenge to current treatments of melanoma and several other cancers. Recently, targeting ERK has evolved as a potentially attractive strategy to overcome this resistance. Herein, we report the design and synthesis of novel series of fused naphthofuro[3,2-*c*]quinoline-6,7,12-triones (**3a-f**) and pyrano[3,2-*c*]quinoline-6,7,8,13-tetraones (**5a-b** and **6**), as potential ERK inhibitors. New inhibitors were synthesized and identified by different spectroscopic techniques and X-ray crystallography. They were evaluated for their ability to inhibit ERK1/2 in an *in vitro* radioactive kinase assay. **3b** and **6** inhibited ERK1 with IC<sub>50</sub>s of 0.5 and 0.19  $\mu$ M, and inhibited ERK2 with IC<sub>50</sub>s of 0.6 and 0.16  $\mu$ M respectively. Kinetic mechanism studies revealed that the inhibitors are ATP-competitive inhibitors where **6** inhibited ERK2 with a K<sub>i</sub> of 0.09  $\mu$ M. Six of the new inhibitors were tested for their *in vitro* anticancer activity against the NCI-60 panel of tumor cell lines. Compound **3b** and **6** were the most potent against most of the human tumor cell lines tested. Moreover, **3b** and **6** inhibited the proliferation of the BRAF mutant A375 melanoma cell with IC<sub>50</sub>s of 3.7 and 0.13  $\mu$ M, respectively. In addition, they suppressed anchorage-dependent colony formation. Treatment of the A375 cell line with **3b** and **6** inhibited the phosphorylation of ERK substrates p-90RSK and ELK-1 and induced apoptosis in a dose dependent manner. Finally, a molecular docking study showed the potential binding mode of **3b** and **6** within the ATP catalytic binding site of ERK.

**Keywords:** naphthafuro-quinoline, naphthafuro-pyranoquinoline, ERK inhibitors, NCI-60 panel, BRAF mutant, Melanoma.

## Introduction

The fused pyranoquinolines have a common structural motif, existing in many naturally occurring and biologically active alkaloids, such as flindersine, oricine, verprisine, and *Araliopsis tabouensis* alkaloids [1,2]. Several derivatives of these alkaloids are being used as pharmaceuticals and agrochemicals. They have been reported to exhibit a wide range of biological activities including anti-inflammatory, anti-allergic, psychotropic, and estrogenic effects [3]. Their broad biological activity has turned them into popular compounds for pharmacological studies [4-7]. Recent studies reported the successful construction of fused tricyclic pyranoquinolines, such as polycyclic using 4-hydroxyquinolone together with different activated ylidenes [8]. Moreover, a multicomponent system has also been used for synthesis based on fused pyranoquinolines [9, 10]. Derivatives of the 1,4-naphthoquinone pharmacophore are known to exhibit pronounced biological and pharmacological activities, including anti-tumor[11], anti-proliferative [12], anti-mycobacterial [13], anti-platelet, anti-inflammatory, anti-allergic [14], anti-malarial [15] and anti-leishmanial activities [16]. Substituted naphtho[2,3-*b*]furan-4,9-diones inhibited hyperproliferation of human keratinocytes and could therefore be potentially useful in the treatment of psoriasis, a common, immune-mediated inflammatory disease [17].

The high frequency of aberrant activity of the RAS/RAF/MEK/ERK cascade found in human cancers, makes this pathway a potential target for treatment [18, 19]. Several potent inhibitors, targeting RAF and MEK kinases have been widely used for BRAF- and RAS- mutant tumors, including vemurafenib, dabrafenib, trametinib and selumetinib [18]. However, tumor regrowth after an initial response is common and is attributed to several mechanisms [20, 21], commonly all involving ERK reactivation. ERK corresponds to a pair of downstream kinases (ERK1 and

ERK2) and represents a terminal signal node for this pathway [22]. Several ERK inhibitors have been discovered and show an ability to overcome resistance [23]. For example, the potent ERK inhibitor BVD-523 (Ulixertinib) showed encouraging antitumor activity in *in vitro* and *in vivo* models of acquired resistance to BRAF and/or MEK targeted inhibitors [24]. A recent dose escalation in-human study of BVD-523, exhibited early evidence for clinical activity in NRAS- and BRAF V600-solid tumor malignancies with acceptable safety and pharmacokinetics behavior [19]. The apparent promise of ERK modulators in human cancer, especially the ones with acquired resistance to BRAF and/or MEK inhibition, encouraged our efforts towards developing a potent and selective ERK inhibitor.

We have utilized the 2,3-dichloro-1,4-naphthoquinone (DCHNQ) moiety in several heterocyclic synthesis programs, including the synthesis of heterocycles having creatinine [25] and thiobarbituric acid [26]. In addition, we synthesized several naphtho-1,3-dithiole derivatives [27] and dibenzo[*b,i*]-thianthrene-5,7,12,14-tetraone derivatives [28]. In our previous studies, we synthesized a series of ethyl pyrano[3,2-*c*]quinoline-4-carboxylates [29], spiro(indoline-3,4'-pyrano[3,2-*c*]-quinoline)-3'-carbonitriles [30], 2,3-bis-(4-hydroxy-2-oxo-1,2-dihydroquinolin-3-yl)succinates and arylmethylene-bis-3,3'-quinoline-2-ones [31]. In addition to the synthesis of two series of *N*-2,3-bis(6-substituted-4-hydroxy-2-oxo-1,2-dihydroquinolin-3-yl)naphthalene-1,4-diones and substituted *N*-(methyl/ethyl)bisquinolinone triethyl-ammonium, that been reported to inhibit ERK2 activity in an *in vitro* kinase assay [32].

In this current project we synthesized a novel series of fused naphthofuro[3,2-*c*]quinoline-6,7,12-triones **3a-f** and pyrano[3,2-*c*]quinoline-6,7,8,13-tetraones **5a-b** and **6** from the reaction of 1,6-disubstituted-4-hydroxy-quinoline-2-ones **1a-f** and 4-hydroxy-pyrano[3,2-*c*]quinoline-4,5(6*H*)-diones **4a-c** with 2,3-dichloro-1,4-naphthoquinone (DCHNQ). The ability of the new

compounds to inhibit the ERK kinase activity was assessed in an in vitro kinase assay and in cells using western blotting. The cytotoxic activity of the synthesized compounds towards the NCI-60 panel of cancer cell lines was determined and the cellular mechanism of the most potent inhibitors was further investigated in A375 melanoma cell line. Finally, the binding features of the synthesized compounds within the ATP-binding site of ERK2 was estimated using molecular docking studies.

## 2. Results and Discussion

### 2.1. Chemistry

Upon mixing equivalent amounts of 2,3-dichloro-1,4-naphthoquinone (DCHNQ, **2**) and 1,6-disubstituted-4-hydroxy-quinoline-2-ones **1a-f**, followed by refluxing in different solvents, such as: NaOEt/EtOH (**Method I**), pyridine (**Method II**) or DMF (**Method III**), naphtho[2',3':4,5]furo[3,2-*c*]quinoline-6,7,12(5*H*)-trione derivatives **3a-f** were obtained as single products (Scheme 1A). Noticeably, the reaction in pyridine (**Method II**) afforded **3a-f** in better yields (85-92%), if compared to the other two methods (Scheme 1A). Structure elucidation of compounds **3a-f** was carried out by IR, <sup>1</sup>H-NMR, <sup>13</sup>C-NMR and mass spectrometry, as well as elemental analyses. The structures of **3c** and **3f**, were confirmed by X-ray structural analysis (Figure 1A and 1B). Afterward, we investigated the reactions of DCHNQ (**2**) and 4-hydroxy-pyrano[3,2-*c*]quinoline-4,5(6*H*)-diones (**4a-c**) under the same conditions mentioned above (Scheme 1B). The reaction of **2** and **4a,b** afforded two 5*H*-naphthalen-[2'',3'':4',5']-furo[3',2':4',5,6]pyrano-[3,2-*c*]quinoline-6,7,8,13-tetraones derivatives **5a, b** as single products. In the same time, the reaction of **2** and **4c** afforded a different product of *syn/anti*-3-(1,4-dioxo-1,4-dihydronaphthalen-2-yl)-4-hydroxy-6-phenyl-2*H*-pyrano[3,2-*c*]-quinoline-2,5(6*H*)-dione (**6**).

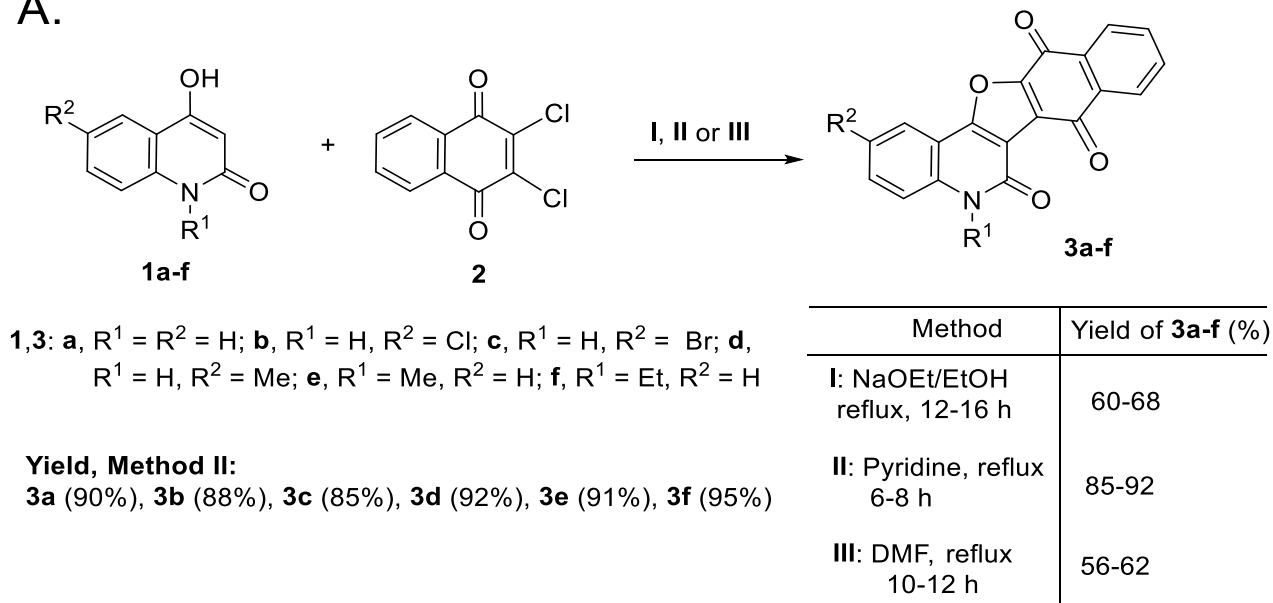


The chemical identities of **5a,b** and **6** was confirmed by IR,  $^1\text{H}$ -NMR,  $^{13}\text{C}$ -NMR, mass spectrometry and elemental analyses.

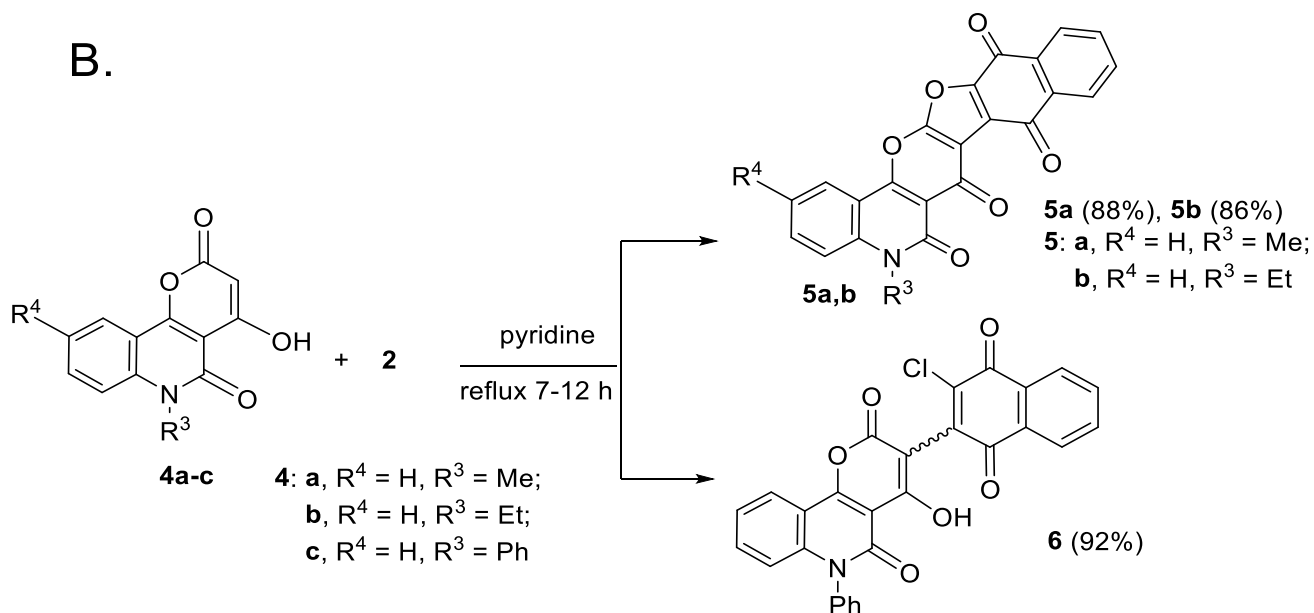
Structure elucidation of compounds **3a-f** was carried out by IR, NMR and mass spectra, besides elemental analyses. For **3a**, its gross formula  $\text{C}_{19}\text{H}_8\text{ClNO}_4$  represents a product from one molecule of **1a** and one molecule of DCHNQ, **2** with elimination two molecules of HCl. Mass spectrum and elemental analysis proved the molecular formula of **3a** as  $\text{C}_{19}\text{H}_9\text{NO}_4$ . The IR spectrum of **3a** showed four characteristic bands at  $\nu = 3210$  (NH), 1700, 1660 (CO), 1596 (Ar-C=C). Resonated double-doublet, doublet and singlet were appeared in the  $^1\text{H}$  NMR spectrum of **3b** at  $\delta_{\text{H}}$  7.65 ( $J = 7.0, 0.8$  Hz) for H-3, 7.50 ( $J = 0.7$  Hz) for H-1 and  $\delta_{\text{H}}$  8.10 ppm for (NH). In  $^{13}\text{C}$  NMR spectrum of **3f**, the two carbonyl carbons appeared at  $\delta_{\text{C}} = 176.0$  and 173.0 ppm. Seven carbon signals were also distinguished in  $^{13}\text{C}$  NMR of **3f** absorbed at  $\delta_{\text{C}} = 160.4, 132.7, 128.6, 127.7, 126.8,$  and 115.5 ppm assigned to C-6, C-9 (C-10), C-3, C-1, C-8 (C-11) and C-4, respectively (Experimental section). The ethyl protons were absorbed in the  $^1\text{H}$  NMR spectrum at  $\delta_{\text{H}} = 1.30$  and 4.47 as quartet and triplet, whereas its carbons resonated in the  $^{13}\text{C}$  NMR spectrum at  $\delta_{\text{C}} = 13.7$  ( $\text{CH}_3$ ) and 47.8 ppm ( $\text{CH}_2$ ) (Experimental section). In the light of the above mentioned findings, we undertook to investigate the reactions of DCHNQ (**2**) with 4-hydroxy-pyrano[3,2-*c*]quinoline-4,5(6*H*)-diones **4a-c** under the same previous condition (Scheme 1B). We have expected that reaction behaves similarly as in the reaction of **1a-f** with **2**. The structure of the obtained 5*H*-naphthalen-[2'',3'':4',5']-furo[3',2':4',5,6]pyrano-[3,2-*c*]quinoline-6,7,8,13-tetraones **5a,b** (Scheme 1B) was only noted in case of the reaction between **4a,b** and **2** (Scheme 1B). Whilst reaction of **4c** with **2** gave *syn/anti*-3-(1,4-dioxo-1,4-dihydronaphthalen-2-yl)-4-hydroxy-6-phenyl-2*H*-pyrano[3,2-*c*]quinoline-2,5(6*H*)-dione (**6**). Compound **6** was obtained as characteristically brown color crystals. Its molecular structure formula is  $\text{C}_{28}\text{H}_{15}\text{NO}_6$ , represents a product from one molecule of DCHNQ and one molecule of **4c** with loss one molecule of HCl. In  $^1\text{H}$  NMR spectrum, the low-field OH- attached to

pyrane ring is at  $\delta_H = 13.90$  ppm. In  $^{13}\text{C}$  NMR spectrum, the distinct carbons assigned as CO (C-1'), C-OH, CO (C-2) and C-O, (C-5), resonated at  $\delta_C = 176.9, 166.1, 163.2$  and  $162.3$  ppm, respectively.

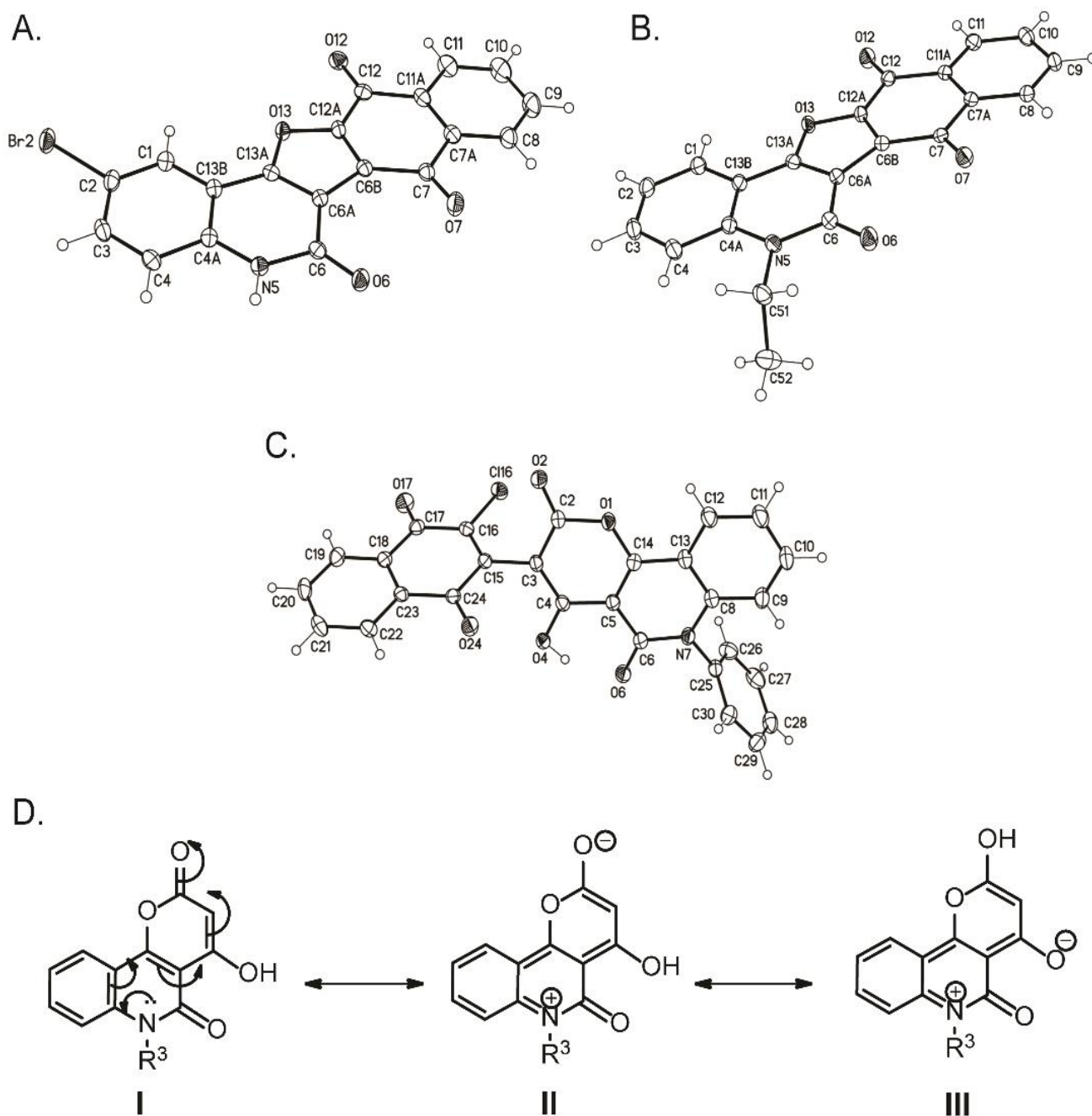
**A.**



**B.**



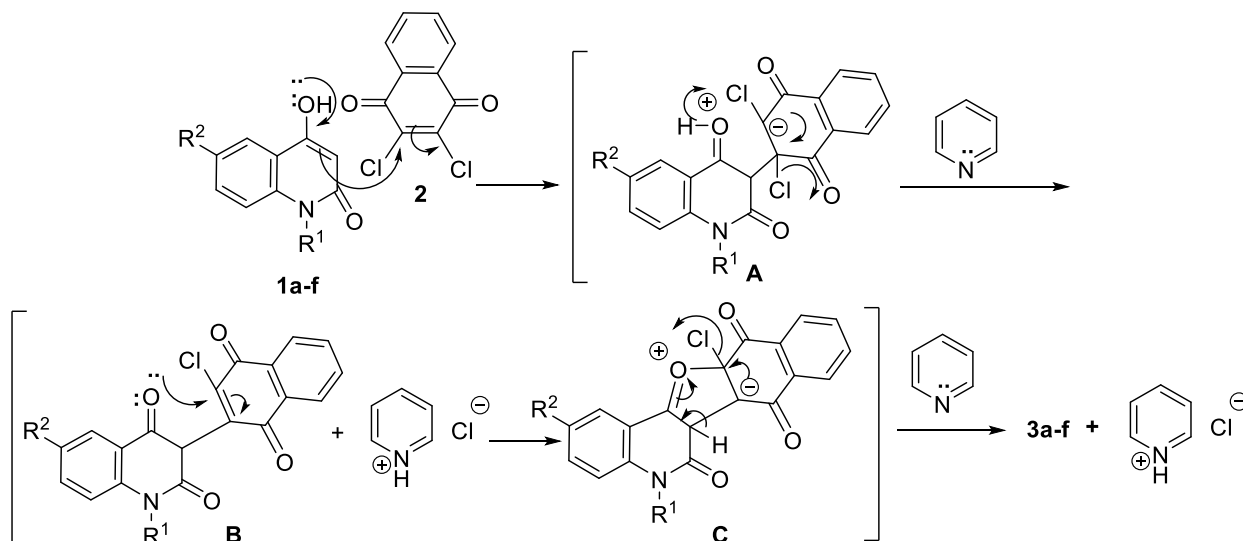
**Scheme 1. (A).** Different methods for preparation of naphthofuro[3,2-*c*]quinoline-6,7,12-triones **3a-f**. **Scheme 1 (B).** Reaction of 4-hydroxy-pyrano[3,2-*c*]quinoline-4,5(6*H*)-diones **4a-c** with **2**.



**Figure 1.** The X-ray structural analysis of (A) **3c** and (B) **3f** and (C) **6**. The X-ray structure of one of the two crystallographic independent molecules of **6**, solvent omitted for clarity and displacement parameters are drawn at 50% probability level. (D) Resonance structures of quinolones **4a,b**.

The same conclusion was confirmed by single crystal X-ray analysis (Figure 1C). The basicity of the *N*-quinolone lone pair in compounds **4a,b**, is responsible for the nucleophilic character of the OH group

that enables the cyclization process. The former is related to the resonance structures **I** to **III** (Figure 1D). Since the *N*-Ph derivative **4c** is of lower basicity compared to **4a,b**, the reaction stops at the step of replacement in the nucleophilic position-3 of the pyrano moiety (Figure 1D).



**Scheme 2.** Mechanism described formation of compounds **3a-f**

The reaction mechanism can be described as nucleophilic attack of CH-3 in **1a-f** to C-2 in **2** to form the Zwitter ion **A** (Scheme 2). Pyridine molecule would then enhance elimination of HCl from **A** to give intermediate **B** and pyridinium salt. Further nucleophilic attach from the oxygen lone pair to vinylic carbon in **B** would give Zwitter ionic intermediate **C** (Scheme 2). Ultimately, a second molecule of pyridine would catalyze the elimination of HCl to give **3a-f** and pyridinium salt (Scheme 2).

## 2.2. Biological evaluation

**2.2.1. Evaluation of the *in vitro* anticancer activity of the new compounds** - Among the synthesized compounds, NCI selected compounds **3a**, **3b** and **3e** from the fused naphthofuro[3,2-*c*]quinoline-6,7,12-trione derivatives and **5a**, **5b** and **6** from the fused naphthofuro-pyrano[3,2-*c*]quinoline-6,7,8,13-tetraone derivatives. Anticancer assays were performed according to the US

NCI protocol (The procedures of the assay are described at (<http://www.dtp.nci.nih.gov>). The compounds were tested against a panel of 60 cancer cell lines, derived from different tumors. Including leukemia, melanoma, lung, colon, central nervous system (CNS), ovarian, renal, prostate and breast cancer. The compounds were incubated with the cells at a concentration of 10  $\mu$ M for 48 h and the cells density were estimated using sulforhodamine B (SRB), a protein binding dye. The results were reported as the growth percent (G%) of the cells that were treated by each compound relative to the cells treated with vehicle, and relative to the number of cells present when the treatment with the compounds started (Table 1). On average, **3a**, **3b** and **3e** exhibited inhibitory effects on most of the leukemia cell lines tested with varied responses. While, in the rest of the tested tumors, compound **3b** showed much more pronounced growth suppressive activity, compared to **3a** and **3e** with an average G% of -4.7, 68 and 74 % respectively.

Nevertheless, in a few cell lines strong growth inhibition and/or lethality were observed by **3a**, specifically in the two leukemia cell lines HL-60(TB) and MOLT-4 and the ovarian cancer cell lines OVCAR-3 and OVCAR-4. Whereas **3e** strongly suppressed the growth of the leukemia cell line MOLT-4 and the ovarian cancer cell line OVCAR-4. Interestingly, **3b** was able to induce a broad tumor cell death for most of the non-small cell lung cancer, colon cancer, CNS cancer, melanoma, ovarian cancer, renal cancer and breast cancer cell lines (Table 1). Even in the cell lines where it was not toxic, **3b** typically exhibited considerably more potent growth inhibition than **3a** and **3e**. Upon testing **5a**, **5b** and **6**, compound **6** showed a major anti-proliferative effect on most of the tested cell lines, with average G% of 35%, whereas compound **5a** and **5b** showed little growth suppressive activity against most of the tested human cancer cell lines with average G1% of 65 and 95% respectively. For example, **5a** induced cell death in few cell lines, including

two ovarian cancer cell lines OVCAR-3 and OVCAR-4, two leukemia cell lines HL-60 and MOLT-4, and one breast cancer cell lines MDA-MB-468. In addition, the growth of the leukemia cell line CCRF-CEM was almost completely inhibited by **5a**.

**Table 1.** Growth percent (G %) of the NCI-60 panel tumor cell lines at  $10^{-5}$  M concentration of compounds **3a**, **3b**, **3e**, **5a**, **5b** and **6**

Tumor cell lines	Growth Percent (G %)					
	<b>3a</b>	<b>3b</b>	<b>3e</b>	<b>5a</b>	<b>5b</b>	<b>6</b>
<b>Leukemia</b>						
CCRF-CEM	20.72	29.04	19.07	92.93	2.47	17.76
HL-60(TB)	2.26	94.52	ND	104.29	-18.8	7.05
K-562	55.20	12.90	68.79	89.61	28.57	26.84
MOLT-4	5.55	18.44	2.39	87.37	-24.49	16.13
RPMI-8226	62.72	4.83	51.06	100.23	33.49	19.65
SR	43.80	33.72	ND	92.01	80.76	11.44
<b>Non-Small Cell Lung Cancer</b>						
A549/ATCC	97.18	-0.05	81.67	85.17	82.36	37.73
EKVX	27.35	15.17	70.67	ND	ND	ND
HOP-62	118.63	-38.70	81.77	80.81	80.29	36.07
HOP-92	71.42	-37.24	100.92	99.17	50.81	80.01
NCI-H226	78.47	-28.80	73.22	88.55	99.44	86.30
NCI-H23	65.95	21.21	78.33	86.15	66.79	38.22
NCI-H322M	89.28	13.98	96.16	91.04	97.72	63.53
NCI-H460	68.27	-69.73	78.50	108.09	83.68	33.57
NCI-H522	54.81	-16.76	50.55	78.37	65.5	19.42
<b>Colon Cancer</b>						
HCC-2998	102.57	65.07	101.82	103.64	100.59	42.85
HCT-116	55.46	-12.24	71.69	99.77	34.6	41.72
HCT-15	44.70	-31.10	85.01	94.13	79.63	66.56
HT29	102.52	66.37	73.69	96.96	63.02	84.18
KM 12	66.22	0.12	91.54	95.63	86.61	18.86
SW-620	89.23	-53.04	86.24	103.1	73.47	18.61
<b>CNS Cancer</b>						
SF-268	91.30	-31.69	95.35	101.09	84.32	34.32
SF-295	92.71	-1.34	ND	101.32	95.07	18.38
SF-539	90.30	-27.99	97.17	93.83	89.92	-5.45
SNB-19	103.72	7.11	93.29	110.38	90.17	27.87
SNB-75	112.98	-9.01	64.39	101.36	119.73	31.77
U251	79.04	-77.55	90.22	104.35	57.67	21.15
<b>Melanoma</b>						
LOX IMVI	56.12	11.13	76.59	95.89	32.39	42.99
MALME-3M	124.29	-51.66	113.45	113.29	112.5	42.00
M14	73.38	10.44	85.59	98.25	89.81	44.74
MDA-MB-435	83.72	10.25	103.73	105.3	95.88	87.80
SK-MEL-2	76.92	31.83	92.64	86.85	79.89	23.06
SK-MEL-28	112.03	-11.84	111.89	107.21	106.96	39.37
SK-MEL-5	79.73	12.31	76.95	97.56	67.42	17.66
UACC-62	88.73	75.08	77.03	93.45	63.95	13.17
<b>Ovarian Cancer</b>						
IGROV1	55.11	-3.63	68.65	65.92	68.31	71.85
OVCAR-3	-14.81	-68.37	21.58	98.93	-16.31	2.15
OVCAR-4	-5.49	-42.04	4.38	97.38	-99.52	18.80
OVCAR-5	102.37	52.70	119.92	102.02	117.77	88.70
OVCAR-8	35.61	-27.45	85.32	100.1	10.25	48.24
SK-OV-3	104.46	1.64	93.55	95.03	102.05	67.28
<b>Renal Cancer</b>						
A498	103.58	80.44	93.29	ND	ND	ND
ACHN	65.70	-14.18	75.49	85.7	79.61	28.55
RXF 393	97.24	-46.34	100.91	87.68	72.63	69.20
SN12C	70.40	-26.26	81.84	125.68	106.07	-14.11
UO-31	60.44	-54.91	54.76	137.02	112.5	64.18
<b>Prostate Cancer</b>						

PC-3	65.49	-33.26	64.38	79.23	81.82	49.16
DU-145	82.02	-45.39	90.97	81.38	42.4	34.21
<b>Breast Cancer</b>						
MCF7	48.82	0.70	68.38	76.73	92.37	51.60
BT-549	73.94	37.99	77.38	104.21	93.67	12.26
T-47D	22.52	-58.11	9.70	83.56	85.06	4.47
MDA-MB-468	-8.43	-32.41	-9.91	64.82	-9.96	-27.29
<b>Average G%</b>	<b>68.19</b>	<b>-4.69</b>	<b>74.32</b>	<b>95.45</b>	<b>65.81</b>	<b>35.49</b>

ND, Not determined

As compound **3b** exhibited the most pronounced inhibitory activity, it was further selected for advanced five dose testing, in which the cytotoxic and/or growth inhibitory effects of the compound were quantified *in vitro* against the full NCI-60 panel of human tumor cell lines using a series of five 10-fold dilutions, ranging from  $10^{-4}$  M to  $10^{-8}$  M. Three dose response parameters were calculated for each cell line, GI<sub>50</sub> (molar concentration required for 50% growth inhibition), TGI (molar concentration leading to total growth inhibition), and LC<sub>50</sub> (molar concentration resulting in 50% cell death).

**Table 2:** The main cytotoxic parameters (GI<sub>50</sub>, TGI and LC<sub>50</sub>) of compound **3b** in  $\mu$ M.

Tumor cell lines	GI <sub>50</sub>	TGI	LC <sub>50</sub>
<b>Leukemia</b>			
CCRF-CEM	0.41	4.86	>100
HL-60 (TB)	1.70	5.25	34.76
K-562	0.37	2.00	50.12
MOLT-4	0.44	3.16	>100
RPMI-8226	0.39	2.63	>100
SR	0.50	3.98	>100
<b>Non-Small Cell Lung Cancer</b>			
A549/ATCC	1.02	2.88	8.32
EKVX	0.25	2.45	26.30
HOP-62	0.20	0.65	3.24
HOP-92	0.15	0.39	1.00
NCI-H226	0.14	0.35	0.87
NCI-H23	0.35	1.82	7.08
NCI-H322M	0.32	1.45	7.24
NCI-H460	0.22	0.49	1.48
NCI-H522	0.32	1.38	8.13
<b>Colon Cancer</b>			
COLO 205	10.47	27.54	72.44
HCC-2998	0.63	2.57	9.12
HCT-116	0.31	1.10	4.57
HCT-15	0.21	0.51	2.00
HT29	3.72	12.88	39.81
KM 12	0.45	3.02	27.54
SW-620	0.33	1.00	7.59
<b>CNS Cancer</b>			
SF-268	0.46	3.98	48.98
SF-295	0.63	2.29	6.61
SF-539	0.23	0.56	2.09
SNB-19	0.31	1.10	6.17
SNB-75	0.16	0.42	1.29
U251	0.27	0.76	2.82
<b>Melanoma</b>			
LOX IMVI	0.32	1.32	3.98
MALME-3M	0.23	0.44	0.85
M14	0.40	1.51	4.57

MDA-MB-435	0.30	1.20	4.07
SK-MEL-2	1.74	5.13	19.95
SK-MEL-28	0.34	1.23	4.68
SK-MEL-5	1.30	1.20	3.72
UACC-257	1.32	3.39	8.51
UACC-62	0.28	1.15	3.98
<b>Ovarian Cancer</b>			
IGROV1	0.22	0.74	3.47
OVCAR-3	0.24	0.56	1.82
OVCAR-4	0.17	0.45	1.51
OVCAR-5	3.47	14.79	40.74
OVCAR-8	0.39	2.29	30.20
NCI/ADR-RES	0.35	1.78	34.67
SK-OV-3	0.35	1.78	5.62
<b>Renal Cancer</b>			
786-0	0.22	0.54	2.45
A498	0.21	0.95	3.55
ACHN	0.20	0.58	2.63
RXF 393	0.21	0.58	2.51
SN12C	0.20	0.47	1.35
TK-10	0.38	1.10	6.03
UO-31	0.19	0.60	2.51
<b>Prostate Cancer</b>			
PC-3	0.18	0.46	1.58
DU-145	0.28	0.78	12.30
<b>Breast Cancer</b>			
MCF7	0.23	1.05	18.62
MDA-MB-231/ATCC	0.17	0.51	2.82
HS 578T	0.26	1.38	>100
BT-549	0.30	1.32	6.76
T-47D	0.26	0.98	5.13
MDA-MB-468	0.25	0.87	4.57

As Table 2 demonstrates, the results indicated that the selected active compound **3b** showed broad spectrum anti-tumor activity against the nine tumor sub-panels tested. It exhibited strong growth inhibitory activity against all human cancer cell lines tested, with GI<sub>50</sub> values mostly in the submicromolar range (0.14-10.47  $\mu$ M, with an average across all cell lines tested of 0.24  $\mu$ M and only 7 cell lines showing GI<sub>50</sub> values >1  $\mu$ M) and TGI values typically in the low micromolar range (0.35-27.54  $\mu$ M, with an average of 1.02  $\mu$ M). Importantly, compound **3b** was also able to induce cell death in the vast majority of the cancer cell lines. The LC<sub>50</sub> values ranged between 0.85 and 72.44  $\mu$ M, with an average of 7.58  $\mu$ M. The cytotoxic effects were strongest in the non-small cell lung cancer lines NCI-H226 (LC<sub>50</sub>=0.87  $\mu$ M), HOP-92 (1.00  $\mu$ M) and NCI-H460 (1.48  $\mu$ M), the CNS cancer line SNB-75 (1.29  $\mu$ M), the melanoma line MALME-3M (0.85  $\mu$ M), the ovarian cancer lines OVCAR-4 (1.51  $\mu$ M) and OVCAR-3 (1.82  $\mu$ M), the renal cancer line SN12C (1.35  $\mu$ M) and the prostate cancer line PC-3 (1.58  $\mu$ M).

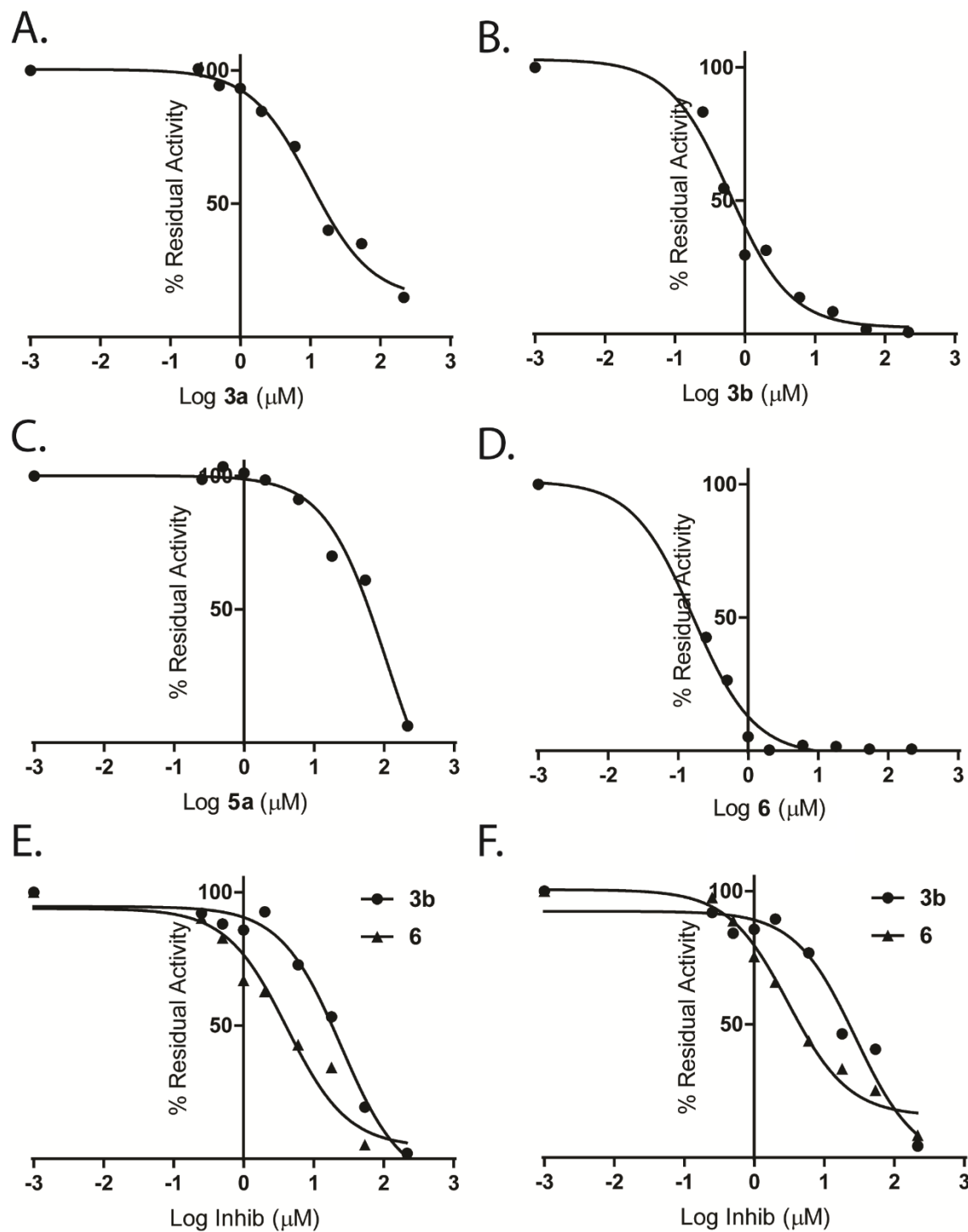


Notably, compound **3b** was also lethal to nearly all of the remaining cancer cell lines, with only five of the lines in the NCI-60 panel not reaching 50% lethality within the concentration range tested (Table 2). In line with the results from the single dose screen, compound **3b** was least efficient against leukemia cells, four of which exhibited an  $LC_{50} > 100 \mu\text{M}$ . The promising anticancer activity observed by these new compounds may be attributed to their activity towards the ERK kinase pathway in these tested tumor cell lines. Accordingly, we decided to go further and test this hypothesis.

### 2.2.2. The new compounds selectively inhibited ERK compared to other MAP kinases –

From the anticancer screening results (Table 1), we selected compounds **3a**, **3b** and **6** to study their molecular mechanism *in vitro* and in cells. Compound **5a** was selected as a negative control compound. First, in an *in vitro* kinase assay, we tested the ability of these compounds to inhibit the activity of ERK1 and ERK2 towards a downstream substrate Ets-1 in the presence of  $100 \mu\text{M}$  ATP. Figure 2A-D show dose response curves for ERK2 inhibition.

As shown in Table 3, **3a**, **3b** and **6** inhibited ERK1 with  $IC_{50}$ s of 9.12, 0.5 and  $0.19 \mu\text{M}$  respectively while **3c** inhibited ERK1 with much higher  $IC_{50}$  of  $95 \mu\text{M}$ . Similar activities were observed for ERK2 with  $IC_{50}$ s of 10.2, 0.6 and  $0.16 \mu\text{M}$  respectively while **5a** inhibited ERK2 with  $IC_{50} > 100 \mu\text{M}$ . To profile the selectivity of these compounds we examined their ability to inhibit other MAP kinases, including JNK2 or p38MAPK $\alpha$ . Compounds **3a** and **5a** did not show any ability to inhibit JNK2 or p38MAPK $\alpha$  (Table 3). Whereas compounds **3b** and **6** showed little tendency to inhibit JNK2 and p38MAPK $\alpha$  (Figure 2E and F). Compound **3b** inhibited JNK2 and p38MAPK $\alpha$  with  $IC_{50}$ s of  $24 \mu\text{M}$  and  $28 \mu\text{M}$ , respectively, revealing a selectivity of around 50-fold towards ERK. Compound **6** inhibited JNK2 and p38MAPK $\alpha$  with  $IC_{50}$ s of  $4.2 \mu\text{M}$  and  $3.1 \mu\text{M}$  respectively, corresponding to around a 20-fold selectivity towards ERK.



**Figure 2.** **3b** and **6** are potent ERK inhibitors in *in vitro* cell-free kinase assays. **3a** (A), **3b** (B), **5a** (C) and **6** (D) inhibited Ets-1 phosphorylation by ERK2 in the in-vitro kinase assay. (E) The effect of **3b** and **6** on the ability of JNK2 to phosphorylate GST-c-Jun (1-221). (F) The effect of

**3b** and **6** on the ability of p38MAPK $\alpha$  to phosphorylate GST-ATF2 (1-115). Data were fitted to Eq. 1 (Methods section).

**Table 3. Selectivity of the tested compounds**

	<b>3a</b>	<b>3b</b>	<b>5a</b>	<b>6</b>
	IC <sub>50</sub> <sup>a</sup> ( $\mu$ M)	IC <sub>50</sub> <sup>a</sup> ( $\mu$ M)	IC <sub>50</sub> <sup>a</sup> ( $\mu$ M)	IC <sub>50</sub> <sup>a</sup> ( $\mu$ M)
ERK1 (100 $\mu$ M ATP)	9.12 $\pm$ 1.1	0.5 $\pm$ 0.09	95 $\pm$ 10.9	0.19 $\pm$ 0.01
ERK2 (100 $\mu$ M ATP)	10.2 $\pm$ 1.2	0.6 $\pm$ 0.1	108 $\pm$ 12.2	0.16 $\pm$ 0.02
ERK2 (10 $\mu$ M ATP)		0.2 $\pm$ 0.01		0.086 $\pm$ 0.005
JNK2	>200	24 $\pm$ 1.24	>200	4.2 $\pm$ 0.9
p38MAPK $\alpha$	>200	27.9 $\pm$ 1.5	>200	3.1 $\pm$ 0.5
A375 Cell Viability		3.7 $\pm$ 0.6		0.13 $\pm$ 0.03

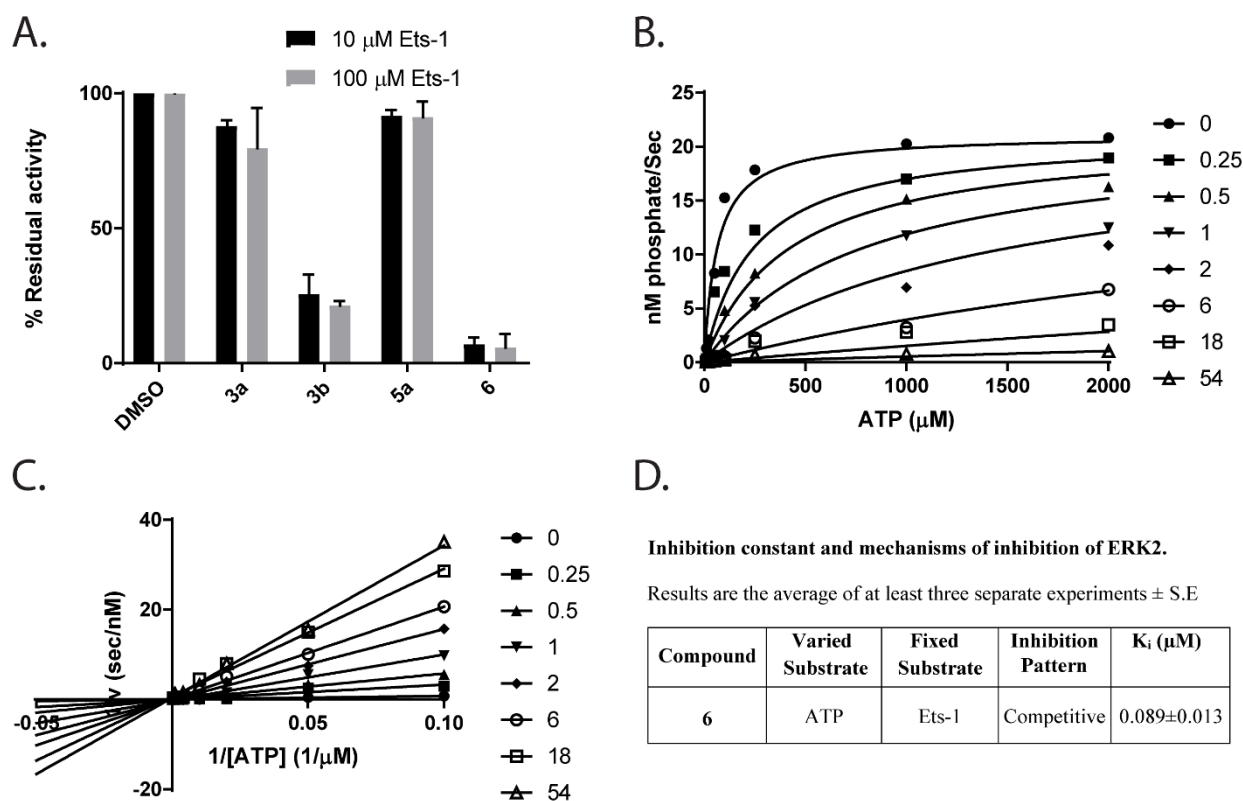
<sup>a</sup>IC<sub>50</sub> Determined as described in Methods section, Data were fitted to equation 1.

Interestingly, the differential ability of the tested compounds to inhibit ERK activity in-vitro correlates to their cytotoxic activity that shown in table 1. **3b** and **6** showed the most potent ERK inhibition and the most pronounced anticancer activity against most of the tested cell lines (average G% of -4.5% and 35% respectively) while compound 3a showed a modest ability to inhibit ERK activity with IC<sub>50</sub> of around 9  $\mu$ M (Table 3) and weak ability to impact the cancer cells growth at 10  $\mu$ M concentration with average %G of 68% (Table 1). The inability of **5a** to exhibit any considerable cytotoxic or anti-proliferative activity (average %G of 95%) was mainly attributed to its limited potency towards inhibiting ERK with IC<sub>50</sub>s of  $\geq$  100 $\mu$ M (Tables 1 and 3).

### 2.2.3. *In vitro* studies of the new inhibitors identify a mechanism of ATP-competitive inhibition

To understand the mechanism of ERK inhibition by the new compounds, we initially tested the effect of varying the concentration of Ets-1 on the ability of the inhibitors to suppress

ERK2 activity. Using excess of Ets-1 (100  $\mu\text{M}$ ) did not rescue the inhibition of ERK2 by 5  $\mu\text{M}$  of **3a**, **3b** or **6** (Figure 3A), as it showed a similar susceptibility to the inhibitors in presence of 10  $\mu\text{M}$  Ets-1 (the  $K_m$  of Ets-1 towards ERK2  $\sim 10 \mu\text{M}$ [33]), suggesting that the binding of the inhibitor does not impact the binding of Ets-1 to ERK2, which binds at the D and F-recruitment sites of ERK2[34, 35]. In order to examine the possibility that the inhibitors may bind the active site of ERK where ATP is known to bind, we determined the IC<sub>50</sub>s of **3b** and **6** towards ERK2 in the presence of 100  $\mu\text{M}$  or 10  $\mu\text{M}$  of ATP (the  $K_m$  of ATP towards ERK2  $\sim 100 \mu\text{M}$ [34]).



**Figure 3.** Mechanism of ERK2 inhibition by the newly synthesized compounds. (A) Higher concentrations of Ets-1 did not impact the ability of **3a**, **3b**, **5a** and **6** to inhibit its phosphorylation by ERK2. 10  $\mu\text{M}$  of each inhibitor were added to 2 nM of activated ERK2 in the presence of either 1 or 10-fold excess over the  $K_m$  of Ets-1 and 100  $\mu\text{M}$  ATP (B) Inhibition of ERK2 activity by **6** at varied fixed concentrations of Mg-ATP (10-2000  $\mu\text{M}$ ) and 50  $\mu\text{M}$  Ets-1 and (C) the double reciprocal plot of  $1/V_0$  vs  $1/[Mg-ATP]$  at varied fixed concentrations of **6** (0-54  $\mu\text{M}$ ) and 50  $\mu\text{M}$  Ets-1. Initial velocities were measured using various (10–2000  $\mu\text{M}$ ) concentrations of Mg-ATP. The data were fitted to a model of competitive inhibition according

to Eq. 2, where  $k_{cat}^{app} = 11 \pm 1.0 \text{ s}^{-1}$ ,  $K_m^{aP}(\text{ATP}) = 63.4 \pm 9.2 \text{ }\mu\text{M}$ ,  $K_i^{aP} = 0.089 \pm 0.1 \text{ }\mu\text{M}$  (**D**) Inhibition constant and mechanism of inhibition of ERK2 by **6**.

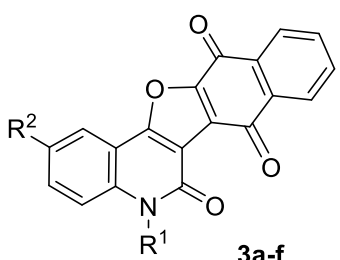
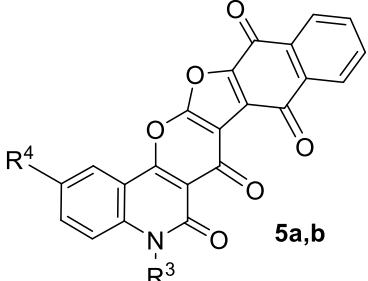
The results shown in table 3 suggest that decreasing the concentration of ATP increased the ‘apparent’ potency of the inhibitor towards ERK2. Compound **3b** showed an IC<sub>50</sub> of 0.6  $\mu\text{M}$  at 100  $\mu\text{M}$  ATP and 0.2  $\mu\text{M}$  in the presence of 10  $\mu\text{M}$  ATP, while **6** showed an IC<sub>50</sub> of 0.16  $\mu\text{M}$  at 100  $\mu\text{M}$  ATP and 0.09  $\mu\text{M}$  in presence of 10  $\mu\text{M}$  ATP. These observations represent the first evidence that these inhibitor bind ERK in the active site, where they are able to prevent ATP from reaching ERK. Furthermore, and to confirm this mechanism, we decided to determine the observed rate constant,  $k_{obs}$ , over a range of ATP concentrations at different fixed concentrations of **6**, in the presence of a saturating concentration of Ets-1 (50  $\mu\text{M}$ ). The double reciprocal plot derived from this study (Figure 3C) is consistent with a mechanism of competitive inhibition, where  $K_i \sim 0.09 \pm 0.01 \text{ }\mu\text{M}$ . According to this model (Figure 3D). Compound **6** binds ERK and abrogates its affinity for ATP without affecting  $k_{cat}$ . The binding mode of **6** to the ERK active site impedes the recognition of ATP by the enzyme.

#### 2.2.4. Structure Activity Relationship

Based on the structural features of the newly synthesized compounds, their cytotoxic activities and their ability to inhibit ERK2 activity *in-vitro* (Table 4), it is obvious that substituents on the quinolone moiety can alter the biological activity of these inhibitors. For example, substituent at *N*-quinoline moiety ( $R^1$  of **3a-f** and  $R^3$  of **5a-b**) seems to decrease their ability to inhibit ERK2 and to suppress their cytotoxic activity. Compound **3a** ( $R^1=\text{H}$ ) showed better ability to inhibit ERK2 and to suppress tumor cell growth, compared to **3e** and **3f** that ( $R^1$  = methyl and ethyl respectively). This demonstrates the important role played by the free NH in the ability of the compounds to inhibit ERK2 and to exhibit anti-tumor activity. Noticeably, the size of  $R^1$  is inversely proportion to the ability to inhibit ERK2 *in vitro*, especially if we

compared the biological activities of 3a, 3e and 3f. Moreover, there is evidence that substituents at the 2 position of the quinolone ring can alter the biological activities of these new derivatives. Interestingly, **3b**, that carries an electron withdrawing Cl at the R2 position showed very high potency towards ERK2 inhibition and tumor cell growth suppression (Table 4), while changing this group to Br (3c) or Me (3d) completely abrogated the ability of these inhibitors to affect ERK2 activity *in vitro*. Finally, compound **6** that formed of a mixture of *syn/anti* isomers of 3-(1,4-dioxo-1,4-dihydronaphthalen-2-yl)-4-hydroxy-6-phenyl-2*H*-pyrano[3,2-*c*]-quinoline-2,5(6*H*)-dione, represents a different scaffolds from **3a-f** or **5a-b**, its potent inhibition of ERK2 activity (IC<sub>50</sub> ~ 0.16 μM) and tumor growth (average G% ~ 35% at 10μM treatment) suggest that its binding mode to ERK2 and its selectivity profile can be different from compounds **3** and **5**.

**Table 4: Structure Activity Relationship**

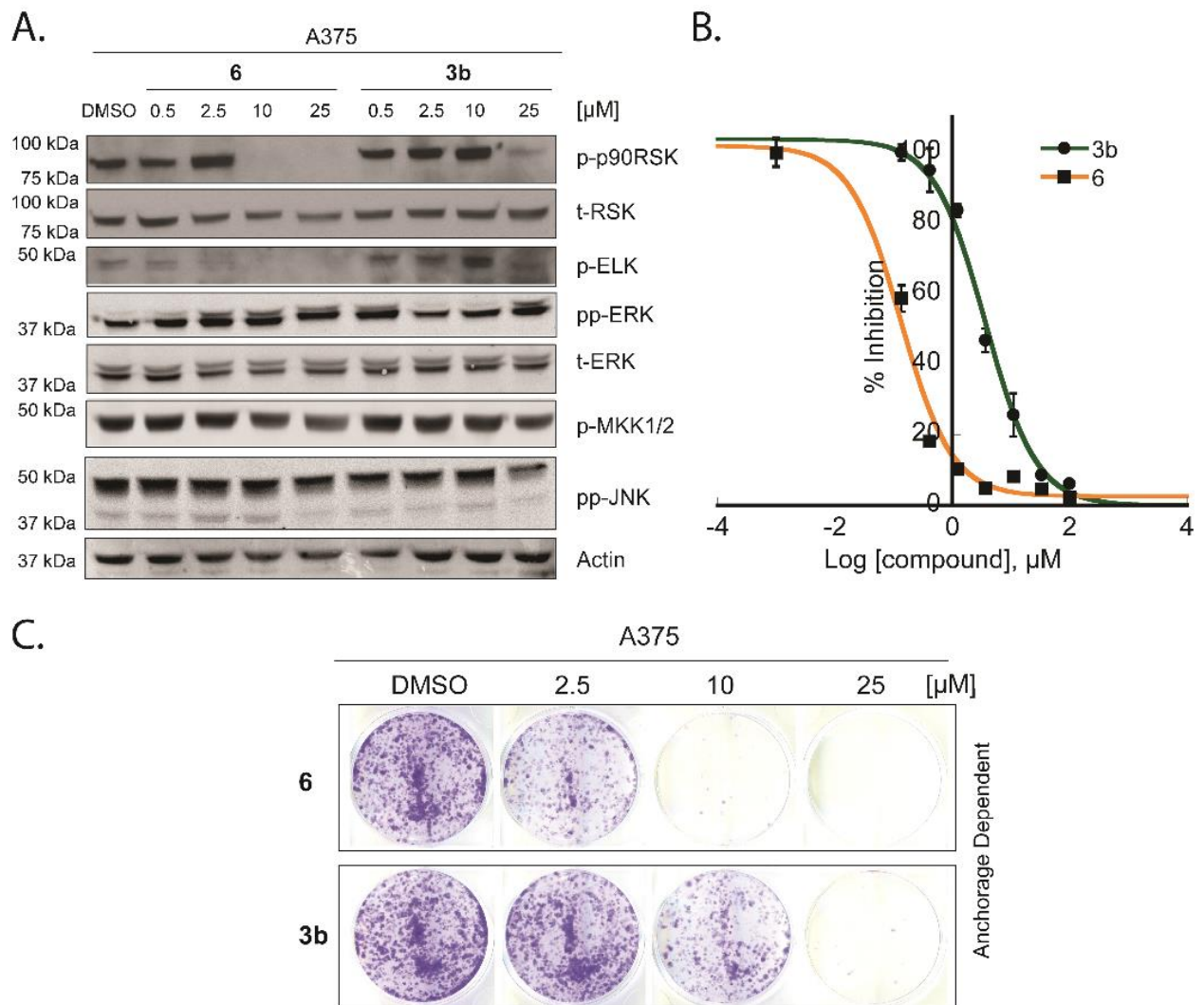
	 <b>3a-f</b>		 <b>5a,b</b>		ERK2 IC <sub>50</sub> <sup>a</sup> (μM) at 100 μM ATP /10 μM Ets-1	NCI Cytotoxicity Screening Average G%
	<b>R<sup>1</sup></b>	<b>R<sup>2</sup></b>	<b>R<sup>3</sup></b>	<b>R<sup>4</sup></b>		
<b>3a</b>	-H	-H			10.2±1.2	68
<b>3b</b>	-H	-Cl			0.6±0.1	-4.5
<b>3c</b>	-H	-Br			>100	ND
<b>3d</b>	-H	-Me			59±8.2	ND
<b>3e</b>	-Me	-H			21±5.6	74
<b>3f</b>	-Et	-H			>100	ND
<b>5a</b>			-Me	-H	>100	95
<b>5b</b>			-Et	-H	8.3±1.5	65
<b>6</b>					0.16±0.02	35

ND, Not determined

<sup>a</sup>IC<sub>50</sub> Determined as described in Methods section, Data were fitted to equation 1.

## 2.2.5. Cellular studies in the BRAF<sup>V600E</sup> mutant human melanoma cell line A375.

**Inhibition of ERK activity towards the downstream substrates** – Melanomas that carry activating BRAF and NRAS mutations exhibit constitutive ERK activity that is known to drive tumorigenesis. Inhibition of ERK activity has been reported to alter the proliferation of melanoma cell lines and inhibit the growth of melanoma tumors[36].



**Figure 4.** Effect of compounds on *BRAF*-mutant A375 melanoma cell line **A.** **6** and **3b** inhibited Elk and p90RSK phosphorylation in the *BRAF*-mutant A375 melanoma cell line. A375 melanoma cells were treated with a DMSO control, different concentrations of **6** or **3b** (0.5-25  $\mu$ M) for 12 hours in serum free media. The MAP kinase pathway was then induced by the addition of EGF (100 nM) for 15 minutes before lysing the cells. Lysates were fractionated by SDS PAGE (10 % gel) and subjected to western blot analysis in order to detect the

phosphorylated forms of p-90RSK, ELK, ERK, MEK1/2 and JNK. **B. 6** is a more potent inhibitor of A375 melanoma cell viability than **3b**. Cells were treated with different doses of each inhibitor and incubated for 72 hours before analysis by the MTS assay. **C. 6** and **3b** inhibited *BRAF*-mutant A375 cells anchorage-dependent growth in a dose dependent manner (Cells were treated as described in the methods section).

Treatment of A375 cells (melanoma cell line expressing BRAF<sup>V600E</sup>) with **3b** or **6**, followed by EGF stimulation resulted in a dose-dependent inhibition of the ERK substrates (p90RSK and ELK) phosphorylation. With no effect on ERK or MKK1/2 phosphorylation or the JNK pathway (Figure 4A). 10  $\mu$ M of compound **6** was enough to inhibit p-90RSK phosphorylation while 2.5  $\mu$ M was enough to inhibit ELK phosphorylation. Compound **3b** inhibited p90RSK at a concentration of 25  $\mu$ M, while inhibited p-ELK at 10  $\mu$ M. Notably, the cellular potencies of the tested compounds matched their relative activity in the *in vitro* kinase assay.

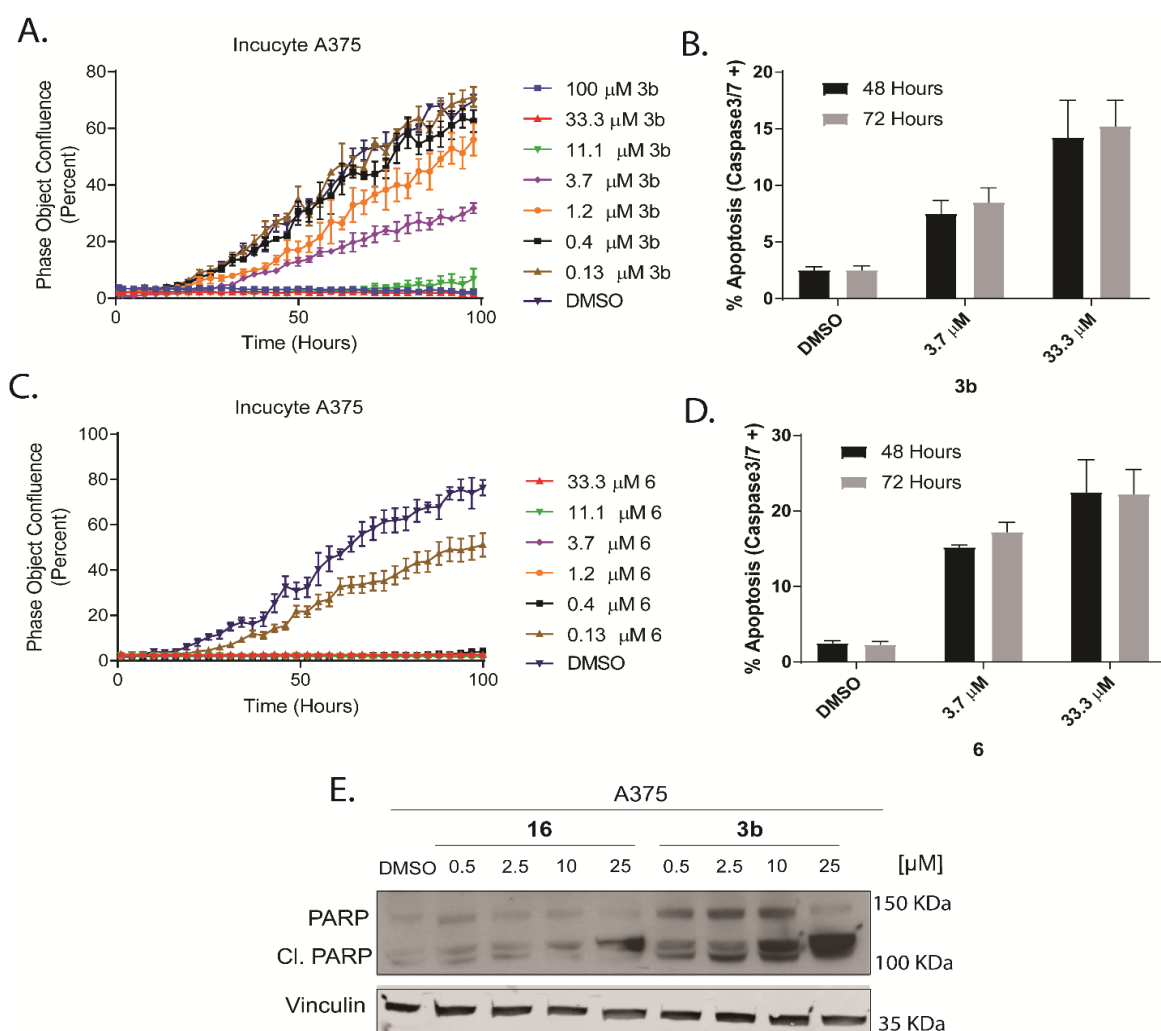
**Effect of the inhibitors on A375 cell viability and colonies formation** – It has been reported that the clinical efficacy that can be produced by any drug targeting the ERK pathway becomes significant after at least 80 % ERK signaling is suppressed.[37] And the degree of ERK inhibition is directly correlated to the inhibition of melanoma cell proliferation.[36] The western blotting experiments emphasized the ability of the new inhibitors to inhibit ERK activity in the A375 cell line. To assess the selectivity of **3b** and **6** in this cell line, we evaluated their antiproliferative activity. **3b** and **6** inhibited A375 proliferation (MTS assay) with IC<sub>50</sub>s of 3.7 and 0.13  $\mu$ M, respectively (Figure 4B and Table 3). Next, we tested the biological effect of these inhibitors on anchorage independent colony formation in soft agar (Figure 4C) that is known to be regulated by ERK kinase activity in melanoma cell lines[38]. Compound **6** started to inhibit melanoma cell colony forming ability at a concentration of 2.5  $\mu$ M while **3b** showed inhibition at 10  $\mu$ M.

**Effect of the compounds on the Proliferation rate of A375 Melanoma cell line** - ERK has been shown to directly regulate over 100 known cellular targets (e.g. as pRSK, MYC and BIM)



that together control tumor cell proliferation, survival, and apoptosis [22]. To test the new inhibitors in a real time proliferation study A375 cells were treated with different dose of each inhibitor and the real time growth confluence was recorded every 1 hour for a total of 90 hours using an IncuCyte Zoom microscope. **3b** and **6** showed dose-dependent inhibition of A375 proliferation (Figure 5A and C) with compound **6** exhibiting the higher potency, compared to **3b**.

**Apoptosis induction** – Melanoma that carry BRAF mutations tends to be more resistant to apoptosis. ERK inhibition has been shown to induce apoptosis in such resistant melanoma.[39].



**Figure 5.** The tested compounds inhibited *BRAF*-mutant A375 melanoma cell proliferation and induced apoptosis. (A-B) IncuCyte analysis of real time growth confluence (imaged every 1 hour) showed dose-response inhibition of A375 growth rates by **6** and **3b**, cells were treated with

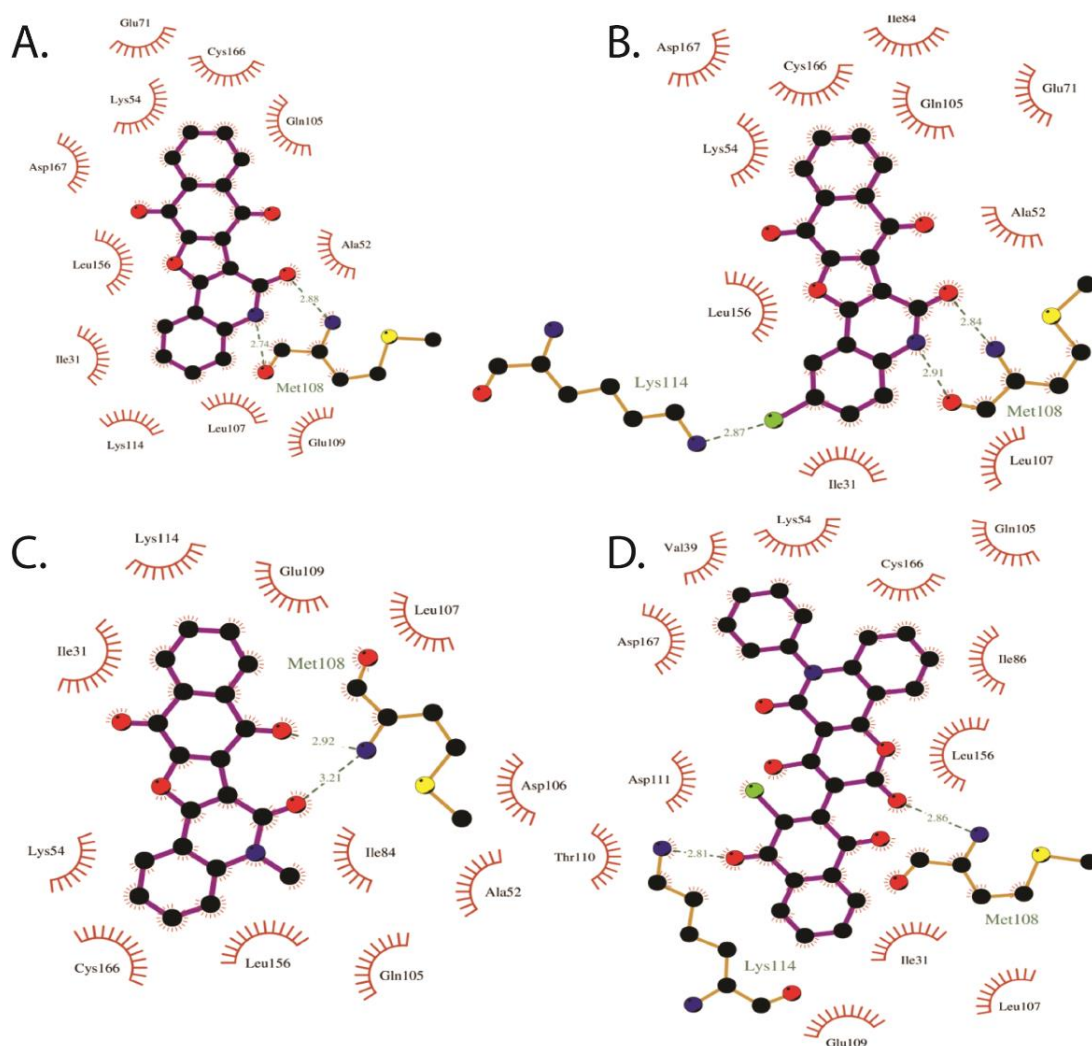
different doses of each inhibitor before starting the IncuCyte imaging. Error bars: SEM ( $n = 3$ ). **(C-D)** Treatment of **6** and **3b** increases the rate of apoptosis of *BRAF*-mutant A375 melanoma cells in a dose-dependent manner. Cells were treated with different doses of each inhibitor, apoptosis was assessed using the IncuCyte Caspase 3/7 reagent and IncuCyte® ZOOM equipment with a  $\times 10$  objective at indicated time points. **(E)** **6** and **3b** induced PARP cleavage in A375 cells. Cells were exposed to different doses of each inhibitor for 12 hours before cell lysis. Protein expression of PARP and cleaved PARP were analyzed by western blot using vinculin as a loading control. (Experiment was repeated two times).

To determine the ability of the new compounds to induce apoptosis, we performed a single cell assay using the IncuCyte microscope. A375 cells were treated with different doses of each inhibitor, plus a fixed concentration of the IncuCyte Caspase3/7 reagent that quantifies the activity of cellular caspase3/7. Stained cells were imaged and counted using the IncuCyte microscope. Interestingly, compounds **3b** and **6** exhibited activation of caspase 3/7 in A375 cell line, at doses of 3.7 and 33.3  $\mu\text{M}$  after 48 and 72 hours of incubation (Figure 5B and D). Moreover, treatment of A375 cells with compound **3b** or **6** resulted an increase in cleaved PARP, another marker of apoptosis induction.[39]. These data support the notion that the induction of apoptosis by these inhibitors is a major mechanism of death that results from ERK pathway inhibition.

### 2.3. Molecular docking calculations

To reveal the binding features of the synthesized compounds with ERK2, molecular docking calculations were performed on the most potent compounds towards the ATP-active site of ERK2 using Autodock4.2 software.[40]. Autodock performance was first validated on an ERK2 crystal structure in complex with a tetrahydropyridopyrimidine amine derivative (*N*-[(1*S*)-1-(3-chloro-4-fluorophenyl)-2-hydroxyethyl]-2-(tetrahydro-2*H*-pyran-4-ylamino)-5,8-dihydropyrido[3,4-*d*]pyrimidine-7(6*H*)-carboxamide) or **2SH** that been reported previously as an ATP competitive inhibitor of ERK [41] (PDB code: 4O6E [41]). Self-docking of **2SH** was performed and the corresponding binding mode was investigated. Compared to the crystal

structure of **2SH**-ERK2 complex, Autodock accurately predicted the binding mode of **2SH** inside the ERK2 active site, forming five essential hydrogen bonds with Lys42, Met108, Lys114 and Asp167. Molecular docking of the synthesized compounds **3a**, **3b**, **3e** and **6** towards the active site of ERK2 was then performed and the corresponding binding energies and features were investigated. According to the docked **3a**-ERK2 structure (Figure 6), **3a** forms two essential hydrogen bonds with Met108 with bond lengths of 2.74 and 2.88 Å. Further interactions including van der Waals and hydrophobic interactions were observed, giving a total docking score of -8.34 kcal/mol. Introduction of a chlorine atom in the 2-position of the quinolone ring increased the binding energy of compound **3b**, relative to the unsubstituted compound **3a**, giving a binding score of -8.82 kcal/mol. The higher binding energy of compound **3b** was attributed to the formation of a further hydrogen bond between chlorine atom and the Lys114.



**Figure 6.** Molecular docking of the synthesized compounds **3a**, **3b**, **3e** and **6** towards ATP-active site of ERK2.

Additionally, introduction of a methyl group on the *N*-quinoline moiety resulted in lower binding energy of compound **3e** (calc. -7.88 kcal/mol). This demonstrates the important role played by the free NH for the formation of the essential hydrogen bond with Met108. Compared to compound **3** derivatives, compound **6** showed better affinity towards ERK2 with docking score of -9.22 kcal/mol. The investigation of the binding mode of compound **6** with ERK2, suggested a different binding mode from compound **3** derivatives. The molecular docking model revealed

that compound **6** formed two hydrogen bonds between the pyrano ring and Met108 and the naphthalene ring and Lys114, with bond lengths of 2.86 and 2.81 Å, respectively (Figure 6).

## 2.4. Drug likeliness and oral bioavailability

Application of in silico computational technology during drug discovery and development offers considerable potential for reducing the number of experimental studies required for compound selection and development. Lipinski's rule of five is commonly used in drug design and development to predict oral bioavailability of potential lead or drug molecules.

**Table 5:** Pharmacokinetic prediction of the synthesized compounds by Molinspiration v2016.10

Compound	miLog P <sup>a</sup>	TPSA <sup>b</sup>	nON <sup>c</sup>	nOHNH <sup>d</sup>	nviolation	Nroth <sup>e</sup>	Mol Vol <sup>f</sup>	MWt <sup>g</sup>	%ABS <sup>h</sup>
<b>3a</b>	3.08	80.14	5	1	0	0	256.10	315.28	81.35%
<b>3b</b>	3.73	80.14	5	1	0	0	269.63	349.73	81.35%
<b>3c</b>	3.86	80.14	5	1	0	0	273.98	394.18	81.35%
<b>3d</b>	3.50	80.14	5	1	0	0	272.66	329.31	81.35%
<b>3e</b>	3.59	69.29	5	0	0	0	273.04	329.31	85.09%
<b>3f</b>	3.97	69.29	5	0	0	1	289.84	343.34	85.09%
<b>5a</b>	4.39	99.50	7	0	0	1	334.38	411.37	74.67%
<b>5b</b>	4.02	99.50	7	0	0	0	317.58	397.34	74.67%
<b>6</b>	4.93	106.59	7	1	0	2	395.84	495.87	72.23%

<sup>a</sup> Logarithm of partition coefficient between n-octanol and water (miLogP).

<sup>b</sup> Topological polar surface area (TPSA).

<sup>c</sup> Number of hydrogen bond acceptors (n-ON).

<sup>d</sup> Number of hydrogen bond donors (n-OHNH).

<sup>e</sup> Number of rotatable bonds (n-roth).

<sup>f</sup> Molecular Volume. <sup>g</sup> Molecular weight (MWt). <sup>h</sup> Percentage of absorption (%ABS).

Molinspiration cheminformatics, (<http://www.molinspiration.com>) online software calculation toolkit, was used to determine the physicochemical parameters *e.g.* lipinski's parameters, topological polar surface area (TPSA) and percentage of absorption (% ABS) of the synthesized compounds. The absorption percentage was calculated by using the following formula: % ABS= 109 - [0.345x TPSA] [42]. According to Lipinski's "rule of five", a candidate molecule will likely to be orally active, if the molecule satisfies the following rule [43]: i) the calculated octanol/water partition coefficient (Log P) < 5, ii) the molecular weight is under 500, iii) number

of hydrogen bond acceptors (notably N and O)  $\leq 10$ , iv) number of hydrogen bond donors (OH and NH groups)  $\leq 5$ . Molecules violating more than one of these rules may have problems with bioavailability (Table 5).[43] Gratifyingly, on close inspection of Table 5, all the synthesized compounds were found to be in compliance with Lipinski rule of five. The *milog P* value of all compounds was found below five, suggesting that the molecules have good permeability across the cell membrane which in turn is needed for generation of bioactivity. Molecular weight was found to be less than 500 and thus these molecules are predicted to be easily transported, diffused and absorbed. In addition, the number of hydrogen bond donors and acceptors were less than 5 and 10, respectively, thus these values are in accordance with Lipinski's rules. TRSA of all titled compounds are observed in the range of (80.14-106.59°A) which is below the limit 160°A, which is a very good indicator of the bioavailability of the synthesized compounds. Meanwhile, the calculated percentage of absorption of all derivatives ranged between (72.23-85.09%), demonstrating that they may have good cell membrane permeability and oral bioavailability.

### 3. Conclusions

A group of novel fused naphthofuro[3,2-*c*]quinoline-6,7,12-triones and naphthofuopyrano [3,2-*c*]quinoline-6,7,8,13-tetraones were synthesized and characterized based on different spectral data, as well as X-ray crystallography for some of the compounds. Six compounds were selected for *in vitro* anticancer screening against the NCI-60 panel of cancer cell lines. Most of the tested compounds showed growth inhibitory activity against at least a subset of the human tumor cell lines at a concentration of 10  $\mu$ M. Compounds, **3b** and **6** had the strongest cytotoxic activity, against the majority of the tested cell lines. To confirm the targeting of the ERK pathway by these inhibitors, we tested all the derivatives in an *in vitro* kinase assay

for ERK2. **3b** and **6** showed the most potent activity towards ERK2 with IC<sub>50</sub>s of 0.6 and 0.16  $\mu$ M respectively. **3b** exhibited 50-fold selectivity towards ERK2, when compared to other MAP kinases while **6** showed 20-fold selectivity. The *in vitro* kinetic mechanism studies revealed an ATP competitive mechanism of inhibition by the new compounds towards ERK. The structure-activity study emphasized that substitution within the quinolone can alter the activity of the compounds towards ERK. The promising potency of **3b** and **6** towards ERK, makes it important to investigate the possible utilization of these inhibitors in RAF mutant melanoma. As a model, we used the A375 cell line that carries the BRAF<sup>V600E</sup> activating mutant that is known to hyperactivate the ERK pathway. **3b** and **6** inhibited ERK substrate phosphorylation in this cell line in a dose-dependent manner. Treating the cells with these inhibitors resulted in potent inhibition of cell proliferation and real time cell growth. **3b** and **6** were potent enough to suppress A375 colony formation (a marker for tumorigenesis), that is known to be regulated by the ERK pathway and induced apoptosis. Finally, the molecular docking results indicated that compounds **3b** and **6** have better affinity towards the ATP-active site of ERK2 with docking scores of -8.82 and -9.22, respectively. Furthermore, this work demonstrates that all the synthesized compounds adhere to the Lipinski rule of five, that is, the synthesized compounds are expected to have good oral bioavailability and a good pharmacokinetic profile. The inhibitor's ability to manipulate ERK signaling in this type of melanoma cell line that harbors constitutive ERK activity, suggests that they represent a valuable group of ERK inhibitors that can be improved by further medicinal chemistry efforts.

## 4. Material and Methods

### 4.1. Chemistry

Melting points, using open glass capillaries on a Gallenkamp melting point apparatus (Weiss-Gallenkamp, Loughborough, UK), were measured without applying any corrections. The IR

spectra were recorded from potassium bromide disks with a FT divece.  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra were measured with a Bruker Avance (400 MHz for  $^1\text{H}$ , and 100 MHz for  $^{13}\text{C}$ ), Institute of Organic Chemistry, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany. The  $^1\text{H}$  and  $^{13}\text{C}$  chemical shifts are given relative to internal standard TMS. Coupling constants are stated in Hz,  $^1\text{H}$ -coupled  $^{13}\text{C}$  spectra were measured using gated decoupling. Correlations were established using  $^1\text{H}$ - $^1\text{H}$  COSY, HMBC and HSQC experiments. Mass spectrometry was performed by electron impact at 70 eV, (FAB-MS): Finnigan MAT 95, Institute of Organic Chemistry, Karlsruhe Institute of Technology, Karlsruhe, Germany. Mass spectra were recorded on Finnigan Fab, 70 eV. TLC was performed on analytical Merck 9385 silica aluminum sheets (Kieselgel 60) with  $\text{Pf}_{254}$  indicator; TLC's were viewed  $\lambda_{\text{max}} = 254$  nm. Elemental analyses were carried out at the Microanalytical Center, Cairo University, Egypt.

#### 4.1.1. Starting materials

1,6-Disubstituted-4-hydroxy-quinoline-2-ones **1a-f** were prepared as previously described. [44, 45] 4-Hydroxy-pyrano[3,2-*c*]quinoline-4,5(6*H*)-diones **4a-c** were prepared according to published procedures [46]. 2,3-Dichloro-1,4-naphthoquinone (**2**) (Aldrich) was purchased from Aldrich.

#### 4.1.2. General Procedure

A mixture of **1a-f** (0.1 mol) or **4a-c** (0.1 mol) and DCHNQ (**2**, 0.1 mol) in 20 mL (10% NaOEt as 1 g Na in 10 mL EtOH), pyridine (10 mL) or DMF (30 mL), was refluxed with stirring. The time peroid until the reactants had disappeared, as mentioned in Scheme 1A and Scheme 1B, was



monitored by TLC. The resulting precipitate was filtered off, washed with ethanol, and recrystallized to give pure crystals of **3a-f**, **5a,b** and **6**.

**4.1.2.1. Naphtho[2',3':4,5]furo[3,2-c]quinoline-6,7,12(5H)-trione (3a).** Yellow crystals (DMF/EtOH), yield: 0.284 g (90%), mp > 360 °C; IR (KBr): 3210 (NH), 1700, 1660 (CO), 1596 (Ar-C=C) cm<sup>-1</sup>; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>):  $\delta_H$  7.50-7.56 (m, 2H, Ar-H), 7.65-7.70 (m, 2H, Ar-H), 7.75-7.80 (m, 2H, Ar-H), 8.00 (s, 1H, NH), 8.12-8.20 (m, 2H, H-9,10); <sup>13</sup>C NMR (100, DMSO-*d*<sub>6</sub>):  $\delta_C$  176.2 (C-7), 173.0 (C-12), 169.1 (C-13a), 160.8 (C-6), 156.3 (C-12a), 136.4 (C-4a), 133.1 (C-6b), 132.7 (C-9, C-10), 132.0 (C-11a), 130.7 (C-6a), 128.9 (C-3), 128.4 (C-7a, C-13b), 127.7 (C-1), 126.6 (C-8, C-11), 124.8 (C-2), 116.0 (C-4); MS (Fab, 70 eV,%): *m/z* 315 (M<sup>+</sup>, 100). *Anal. Calcd. for* C<sub>19</sub>H<sub>9</sub>NO<sub>4</sub>: C, 72.38; H, 2.88; N, 4.44. *Found*: C, 72.51; H, 3.01; N, 4.39.

**4.1.2.2. 2-Chloronaphtho[2',3':4,5]furo[3,2-c]quinoline-6,7,12(5H)-trione (3b).** Yellow crystals (DMF/H<sub>2</sub>O), yield: 0.307 g (88%), mp = 330-2 °C; IR (KBr): 3210 (NH), 3065 (Ar-CH), 1700, 1667 (CO), 1593 (Ar-C=C) cm<sup>-1</sup>; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>):  $\delta_H$  7.50 (d, 1H, *J* = 0.7 Hz, H-1), 7.65 (dd, 1H, *J* = 7.0, 0.8 Hz, H-3), 7.86-7.90 (m, 3H, Ar-H), 8.10 (s, 1H, NH), 8.15-8.20 (m, 2H, Ar-CH); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>):  $\delta_C$  176.4 (C-7), 173.0 (C-12), 169.2 (C-13a), 160.2 (C-6), 156.3 (C-12a), 134.5 (C-4a), 133.1 (C-6b), 132.7 (C-9), 132.0 (C-10), 132.2 (C-11a), 130.3 (C-6a), 130.4 (C-2), 129.8 (C-13b), 129.0 (C-3), 128.4 (C-7a), 127.6 (C-1), 126.6 (C-8, C-11), 123.5 (C-4); MS (Fab, 70 eV,%): *m/z* 351 (M<sup>+2</sup>, 38), 349 (M<sup>+</sup>, 100). *Anal. Calcd. for* C<sub>19</sub>H<sub>8</sub>ClNO<sub>4</sub>: C, 65.25; H, 2.31; N, 4.01. *Found*: C, 65.36; H, 2.19; N, 3.98.

**4.1.2.3. 2-Bromonaphtho[2',3':4,5]furo[3,2-c]quinoline-6,7,12(5H)-trione (3c).** Yellow crystals (DMF/DMSO), yield: 0.334 g (85%), mp = 330-2 °C; IR (KBr): 3195 (NH), 3065 (Ar-CH), 1696, 1667 (CO), 1593 (Ar-CH) cm<sup>-1</sup>; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>):  $\delta_H$  7.37 (d, 1H, *J* = 0.8

Hz, H-1), 7.75 (dd, 1H,  $J = 7.0, 0.8$  Hz, H-3), 7.86-7.92 (m, 3H, Ar-H), 8.10-8.15 (m, 2H, Ar-H), 8.25 (bs, 1H, NH);  $^{13}\text{C}$  NMR (100 MHz, DMSO- $d_6$ ):  $\delta_{\text{C}}$  176.5 (C-7), 173.0 (C-12), 169.2 (C-13a), 160.1 (C-6), 156.0 (C-12a), 135.2 (C-4a), 133.1 (C-1), 132.8 (C-6b), 132.4 (C-9, C-10), 131.6 (C-11a), 131.2 (C-3), 130.5 (C-6a), 130.0 (C-13b), 128.2 (C-7a), 126.6 (C-8, C-11), 124.2 (C-4), 117.4 (C-2); MS (Fab, 70 eV,%):  $m/z$  394 ( $\text{M}^+$ , 36), 392 ( $\text{M}^+$ , 100), 351 (65), 352 (55). *Anal. Calcd. for*  $\text{C}_{19}\text{H}_8\text{BrNO}_4$ : C, 57.89; H, 2.05; N, 3.55. *Found*: C, 58.02; H, 2.11; N, 3.47.

**4.1.2.4. 2-Methylnaphtho[2',3':4,5]furo[3,2-*c*]quinoline-6,7,12(5*H*)-trione (3d).** Yellow crystals ( $\text{CHCl}_3$ /hexane), yield: 0.302 g (95%), mp > 360 °C; IR (KBr): 3194 (NH), 3060 (Ar-CH), 2921-2810 (Aliph.-CH), 1687, 1665 (CO), 1590 (Ar-C=C)  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz, DMSO- $d_6$ ):  $\delta_{\text{H}}$  2.30 (s, 3H,  $\text{CH}_3$ ), 7.20 (dd, 1H,  $J = 7.0, 1.0$  Hz, H-3), 7.72 (d, 1H,  $J = 0.8$  Hz, H-1), 7.80-7.90 (m, 3H, Ar-CH), 8.20-8.25 (m, 3H, Ar-H, NH);  $^{13}\text{C}$  NMR (100 MHz, DMSO- $d_6$ ):  $\delta_{\text{C}}$  176.0 (C-7), 173.0 (C-12), 169.0 (C-13a), 160.8 (C-6), 156.3 (C-12a), 134.1 (C-5), 133.2 (C-4a), 133.0 (C-6b), 132.6 (C-9, C-10), 132.0 (C-11a), 130.4 (C-6a), 130.2 (C-1), 129.0 (C-3), 128.2 (C-7a), 128.0 (C-13b), 126.5 (C-8, C-11), 122.0 (C-4), 21.6 ( $\text{CH}_3$ ); MS (Fab, 70 eV,%):  $m/z$  329 ( $\text{M}^+$ , 100), 90 (10). *Anal. Calcd. for*  $\text{C}_{20}\text{H}_{11}\text{NO}_4$ : C, 72.95; H, 3.37; N, 4.25. *Found*: C, 72.88; H, 3.55; N, 4.13.

**4.1.2.5. 5-Methylnaphtho[2',3':4,5]furo[3,2-*c*]quinoline-6,7,12(5*H*)-trione (3e).** Yellow crystals DMF/MeOH, yield: 0.282 g (91%), mp 350-2°C; IR (KBr): 3060 (Ar-CH), 2940-2870 (Aliph.-CH). 1699, 1671 (CO), 1590 (Ar-C=C)  $\text{cm}^{-1}$ ;  $^1\text{H}$  NMR (400 MHz, DMSO- $d_6$ ):  $\delta_{\text{H}}$  3.75 (s, 3H,  $\text{CH}_3$ ), 7.40-7.50 (m, 2H, Ar-CH), 7.70-7.73 (m, 2H, Ar-CH), 8.00-8.34 (m, 4H, Ar-H);  $^{13}\text{C}$  NMR (100 MHz, DMSO- $d_6$ ):  $\delta_{\text{C}}$  176.5 (C-7), 173.0 (C-12), 169.2 (C-13a), 161.1 (C-6), 156.3 (C-12a), 134.3 (C-4a), 133.1 (C-6b), 132.7 (C-9, C-10), 132.0 (C-11a), 130.7 (C-6a), 128.9 (C-3), 128.4 (C-7a, C-13b), 127.7 (C-1), 126.6 (C-8, C-11), 124.8 (C-2), 115.5 (C-4), 37.9

(CH<sub>3</sub>); MS (Fab, 70 eV,%):  $m/z$  329 (M<sup>+</sup>, 100), 90 (15). *Anal. Calcd. for* C<sub>20</sub>H<sub>11</sub>NO<sub>4</sub>: C, 72.95; H, 3.37; N, 4.25. *Found*: C, 73.08; H, 3.33; N, 4.43.

**4.1.2.6. 2-Ethynaphtho[2',3':4,5]furo[3,2-*c*]quinoline-6,7,12(5*H*)-trione (3f).** Yellow crystals, yield: 0.326 g (95%), mp 310 °C; IR (KBr): 3036 (Ar-CH), 2290 (Aliph.-CH), 1688, 1670 (CO), 1582 (C=C) cm<sup>-1</sup>; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>):  $\delta_H$  1.30 (t, 3H,  $J$  = 7.0 Hz, CH<sub>3</sub>), 4.47 (q, 2H, CH<sub>2</sub>,  $J$  = 7.0 Hz), 7.45-7.50 (m, 2H, Ar-CH), 7.65-7.70 (m, 2H, Ar-H), 7.88-7.94 (m, 4H, Ar-H); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>):  $\delta_C$  176.0 (C-7), 173.0 (C-12), 169.0 (C-13a), 160.4 (C-6), 156.2 (C-12a), 134.2 (C-4a), 133.0 (C-6b), 132.7 (C-9, C-10), 132.0 (C-11a), 130.8 (C-6a), 128.6 (C-3), 128.4 (C-7a, C-13b), 127.7 (C-1), 126.6 (C-8, C-11), 124.8 (C-2), 115.5 (C-4), 47.8 (CH<sub>2</sub>), 13.7 (CH<sub>3</sub>); MS (Fab, 70 eV,%):  $m/z$  343 (M<sup>+</sup>, 100). *Anal. Calcd. for* C<sub>21</sub>H<sub>13</sub>NO<sub>4</sub>: C, 73.46; H, 3.82; N, 4.08. *Found*: C, 73.29; H, 3.75; N, 4.25.

**4.1.2.7. 5-Methyl-5*H*-naphthalen[2'',3'':4',5']furo[3',2':4',5,6]pyrano[3,2-*c*]quinoline-6,7,8,13-tetraone (5a).** Yellow crystals, yield: 0.342 g (86%), mp 315 °C; IR (KBr): 3044 (Ar-CH), 2985 (Aliph.-CH), 1730, 1715, 1679 (CO), 1600, 1594 (Ar-C=C) cm<sup>-1</sup>; <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>):  $\delta_H$  3.4 (s, 3H, N-CH<sub>3</sub>), 7.45-8.21 (m, 8H, Ar-H); <sup>13</sup>C NMR (1000 MHz, DMSO-*d*<sub>6</sub>):  $\delta_C$  176.0, 173.0, 170.2, 162.0 (CO), 160.0, 156.0, 135.1, 134.2, 133.0 (Ar-C), 132.4 (Ar-2CH), 128.0 (Ar-C), 127.7, 126.8, 126.6 (Ar-CH), 126.0, 125.0 (Ar-C), 124.0, 122.8, 116.2 (Ar-CH), 115.8, 115.4 (Ar-C), 29.0 (CH<sub>3</sub>-N-methyl); MS (Fab, 70 eV,%):  $m/z$  397 (M<sup>+</sup>, 100). *Anal. Calcd. for* C<sub>23</sub>H<sub>11</sub>NO<sub>6</sub>: C, 69.53; H, 2.79; N, 3.53. *Found*: C, 69.66; H, 2.81; N, 3.45.

**4.1.2.8. 5-Ethyl-5*H*-naphthalen[2'',3'':4',5']furo[3',2':4',5,6]pyrano[3,2-*c*]quinoline-6,7,8,13-tetraone (5b).** Yellow crystals, yield: 0.361 g (88%), mp 308 °C; IR (KBr): 3190 (Ar-CH), 2980 (Aliph-CH), 1730, 1720, 1669 (CO), 1605, 1585 (Ar-C=C) cm<sup>-1</sup>; <sup>1</sup>H NMR (400MHz,

DMSO- $d_6$ ):  $\delta_H$  = 8.19-8.16 (m, 3H), 7.94-7.92 (m, 2H), 7.80-7.78 (m, 2H), 7.47 (dd, 1H,  $J$  = 6.8, 6.4), 4.42 (q, 2H,  $J$  = 6.9 Hz), 1.29 (t, 3H,  $J$  = 6.9 Hz);  $^{13}\text{C}$  NMR (100 MHz, DMSO- $d_6$ ):  $\delta_C$  = 177.9 (C=O, C-8), 174.7 (C=O, C-13), 173.6 (C=O, C-7), 162.3 (C=O, C-6), 158.1 (C-15A), 155.6 (C-14A), 153.1 (C-13A), 138.9 (C-4A), 134.5 (C-7B, HSQC  $\delta_H$  7.94), 134.0 (C-12A), 133.3 (C-11), 132.7 (C-10, HSQC  $\delta_H$  7.80), 126.9 (C-3), 126.8 (C-9, HSQC:  $\delta_H$  = 8.19), 126.0 (C-12), 125.9 (C-2), 124.2 (C-2), 122.8 (C-8A), 122.3 (C-7A), 115.8 (C-6A, HSQC:  $\delta_H$  = 7.47), 111.5 (C-6A), 110.7 (C-4), 37.1 (CH<sub>2</sub>, HSQC:  $\delta_H$  = 4.42), 12.8 (CH<sub>3</sub>, HSQC:  $\delta_H$  = 1.29). MS (Fab, 70 eV, %):  $m/z$  411 ( $M^+$ , 25), 89 (22). *Anal. Calcd. for* C<sub>24</sub>H<sub>13</sub>NO<sub>6</sub>: C, 70.07; H, 3.19; N, 3.40. *Found*: C, 70.22; H, 3.33; N, 3.55.

**4.1.2.9. 3-(3-Chloro-1,4-dioxo-1,4-dihydronaphthalen-2-yl)-4-hydroxy-6-phenyl-2H-pyrano[3,2-*c*]quinoline-2,5(6H)-dione (6).** Brown crystals, yield: 0.457 g (92%), mp 280 °C; IR (KBr): 3441 (OH), 3044 (Ar-CH), 1727, 1676 (CO), 1594 (Ar-C=C), cm<sup>-1</sup>;  $^1\text{H}$  NMR (400 MHz, DMSO- $d_6$ ):  $\delta_H$  13.90 (br, s, 1H, OH), 8.50-7.50 (m, 13H, Ar-H);  $^{13}\text{C}$  NMR (100 MHz, DMSO- $d_6$ ):  $\delta_C$  179.9, 177.0 (CO), 166.1 (C-OH), 163.2 (CO, C-2), 162.3 (CO, C-5), 157.8 (C-10a), 145.9 (C-2'), 140.3 (Ph-C), 138.4 (C-6a), 135.3 (C-4'a, 8'a), 132.0, 131.2, 131.0, 130.3 (Ar-CH), 130.0, 128.2, 127.1, 124.6 (Ar-2CH), 122.6 (Ar-CH-*p*), 117.0 (C-9), 113.0 (C-4b), 99.5 (C-4a), 95.8 (C-3); MS (Fab, 70 eV,%):  $m/z$  497 ( $M^{+2}$ , 34), 495 ( $M^{+2}$ , 100), 89 (22). *Anal. Calcd. for* C<sub>28</sub>H<sub>14</sub>ClNO<sub>6</sub>: C, 67.84; H, 2.85; N, 2.82. *Found*: C, 67.77; H, 2.99; N, 2.76.

## 4.2. Biological activity assessment

### 4.2.1. Anticancer activity

The methodology of the NCI anticancer screening has been described in details at (<http://www.dtp.nci.nih.gov>). Briefly, the primary anticancer assay was performed against the

NCI-60 panel of approximately 60 human tumor cell lines, derived from nine neoplastic diseases, in accordance with the protocol of the Developmental Therapeutics Program, National Cancer Institute, Bethesda. In the one-dose screen, cells were seeded into 96-well plates at densities between 5 000 and 40 000 cells (depending on the doubling time of the cell line) and 24 h later the test compounds were added to the culture at a single concentration ( $10^{-5}$  M) for 48 h. End point determinations were made spectrophotometrically, based on the protein binding dye, sulforhodamine B (SRB). Results for each tested compound were reported as the percent of growth of the treated cells when compared to the untreated control cells and to the number of cells at time zero. A growth percent value between 0 and 100 indicates growth inhibition, e.g. a growth percent of 30 corresponds to 70% growth inhibition; negative values indicate lethality (lower cell number than at time zero), with -30% meaning 30% lethality.

The cytotoxic and/or growth inhibitory effects of the most active compounds in the one-dose screen were tested in vitro at five different concentrations ranging from  $10^{-4}$  to  $10^{-8}$  M (five-dose screen). Seven absorbance measurements for each cell line were made: time zero (Tz), control growth in the absence of drug (C), and test growth in the presence of the drug at the five concentration levels (Ti)]. The percentage growth was calculated at each of the drug concentrations levels. Percentage growth inhibition was calculated as:  $[(Ti - Tz)/(C - Tz)] \times 100$  for concentrations for which  $Ti \geq Tz$ , and as  $[(Ti - Tz)/Tz] \times 100$  for concentrations for which  $Ti < Tz$ . Three-dose response parameters were calculated for each compound. Growth inhibition of 50% (GI<sub>50</sub>) was calculated from  $[(Ti - Tz)/(C - Tz)] \times 100 = 50$ , which is the drug concentration resulting in a 50% lower net protein increase in the treated cells (measured by SRB staining) as compared to the net protein increase seen in the control cells. The drug concentration resulting in total growth inhibition (TGI) was calculated from  $Ti = Tz$ . The LC<sub>50</sub> (concentration of drug

resulting in a 50% reduction in the measured protein at the end of the drug treatment as compared to that at the beginning), indicating a net loss of cells following treatment, was calculated from  $[(Ti - Tz)/Tz] \times 100 = -50$ . Values were calculated for each of these three parameters if the level of activity was reached; however, if the effect was not reached, the value for that parameter was expressed as more than the maximum concentration tested. The lowest values are obtained with the most sensitive cell lines.

#### **4.2.2. Biochemistry**

***Expression, Purification and Activation of MAP Kinases*** – Activated ERK2 (Rattus norvegicus mitogen activated protein kinase 1, GenBank accession number NM\_053842) was expressed, purified and activated as previously reported in Kaoud et. al [33]. Activated ERK1 were expressed, purified and activated as mentioned in Callaway et al [47]. Full length human JNK2 $\alpha$ 2 (GenBank accession number NM\_002752) was expressed and purified following previously published protocol [48, 49]. *p38MAPK $\alpha$*  was expressed, purified and activated as described previously [50]. The activated kinases were all stored in buffer [25 mM HEPES (pH 7.5), 50 mM KCl, 0.1 mM EDTA, 0.1 mM EGTA, 2 mM DTT and 10-20% (v/v) glycerol] at -80 °C.

***Expression, Purification of protein substrates His-Ets-1 (1-138), GST-C-Jun (1-221) and GST-ATF2 (1-115)*** - His-Ets-1 (1-138) was expressed and purified according to Kaoud et. al previously published protocol [33]. GST-c-Jun (1-221) was expressed and purified according to Yan et al method [49]. GST-ATF2 (1-115) was expressed and purified according to Szafranska et al protocol [50].

***Kinase activity assay*** – MAP kinase assays were performed following Kaoud et al previously reported method [51]. To summarize, all assays were conducted at 28-30 °C in kinase assay

buffer (25 mM HEPES buffer-pH 7.5, 50 mM KCl, 0.1 mM EDTA, 0.1 mM EGTA, 2 mM DTT, 11 mM MgCl<sub>2</sub> and 10 µg mL<sup>-1</sup> BSA) containing different concentrations of each inhibitor with a final DMSO concentration of 5%. To estimate the IC<sub>50</sub> of each tested inhibitor towards the activity of different MAP kinases, 2 nM active ERK1 or ERK2 was assayed with 10 µM Ets1 (1-

$$V_0 = V_{\infty} - \left( V_{\infty} \frac{i}{i + (K_{50})} \right) + V' \quad \text{Equation 1}$$

138) protein substrate. 20 nM active JNK2α2 was assayed with 2 µM GST-c-Jun (1–221) as protein substrate. 10 nM active *p38MAPKα*, was assayed with 10 µM GST-ATF2 (Δ 1-115) protein substrate. In all

the assays, the reaction was started by the addition of radio labeled 10 or 100 µM [<sup>32</sup>P] ATP (100-1000 c.p.m. pmol<sup>-1</sup>). In order to estimate the IC<sub>50</sub> of each tested inhibitor, dose-response curves for data confirming to inhibition were fitted to equation 1.

The parameters used in deriving equation 1 are defined as follows; *i*, concentration of inhibitor I; *V*<sub>0</sub>, observed rate; *V*<sub>∞</sub>, is the observed rate in the absence of inhibitor, *V'* is the observed rate constant at saturating inhibitor, *I*, *K*<sub>50</sub> is the concentration that leads to half the maximal change in *V*<sub>0</sub>.

**Steady-state kinetic experiments** – All assays were performed as described in the kinase activity assay section and as previously reported by Kaoud et al [51], the concentrations of Mg-ATP and compound **6** were varied at fixed Ets-1 concentration level of *K<sub>m</sub>*. Plots of the product against time were employed to calculate the initial rate for each tested condition. Reciprocal plots of 1/*v* against 1/*s* were checked for linearity. Kinetic constants values were estimated using GraphPad

$$\frac{V_0}{V_{\max}^{\text{app}}} = \frac{s}{K_{\text{mS}}^{\text{app}} \left( 1 + i / K_{\text{ic}}^{\text{app}} \right) + s} \quad \text{Equation 2}$$

Prism software where the kinetic data were globally fitted to equation 2;

The parameters used in deriving equation 2 are defined as follows;  $V_o$ , observed rate;  $V_{max}^{app}$ , apparent maximum rate;  $s$ , concentration of substrate S;  $K_m^{ap}$ , apparent Michaelis constant for substrate S;  $i$ , concentration of inhibitor I;  $K_{ic}^{ap}$ , apparent competitive inhibition constant for inhibitor I.

#### **4.2.3. Anticancer activity assays:**

**Cell culture** – *BRAF*-mutant A375 melanoma cell line was maintained in RPMI media (Invitrogen) containing 10% (v/v) heat inactivated FBS-US grade (Invitrogen), 1X Glutamax (Invitrogen), 100  $U/mL^{-1}$  penicillin and 100  $gmL^{-1}$  streptomycin (Invitrogen). Cells was incubated in a humidified 5% CO<sub>2</sub> incubator at 37 °C.

**Viability assays** – To estimate the effect of each tested inhibitor on A375 cell viability, 2000 cells were seeded in each well of 96 well plate, cells were treated with different doses of each compound and incubated for 72 hours before performing the MTS assay (CellTiter 96® Aqueous One Solution Cell Proliferation Assay from Promega) following the manufacturer assay. All experiments were done in triplicate.

**Colony formation assay** – For every tested inhibitor, 1000 A375 cells were seeded in each 60 mm TC plate. Cells were incubated for 24 hours to adhere then treated with different doses of each compound and incubated for additional 10-14 days. Plates were washed with 1X PBS, fixed by 4% paraformaldehyde for 15 minutes at room temperature, washed with PBS then stained with 0.2% crystal violet in 20% methanol/80% water for 10 more minutes. Plates were washed excessively by distilled water then imaged under microscope.

**Western Blotting** - For Western blotting, cells were seeded at 1000,000 cells per well in a 6-well plate and incubated for 24 hours before treatment with DMSO or different doses of each



compound for 4 or 12 hours. Cells were induced with 100 nM EGF for 10-15 minutes before lysis. Cells were washed by 1X PBS (Invitrogen) then lysates were prepared in M-PER™ Mammalian Protein Extraction Reagent (Thermo-Fisher). After centrifuging the lysates, the protein concentration of each supernatant was estimated using Bradford analysis (Bio-Rad). 60 µg of each lysate were fractionated on a 10% SDS polyacrylamide gel (Bio-Rad) and transferred to Hybond-P PVDF Membrane (GE Healthcare). Primary antibodies were incubated overnight at 4 °C using 1:1000 anti-phospho-p90RSK (Thr573) rabbit polyclonal Abs (Cell Signaling Technology); 1:1000 anti- RSK1/RSK2/RSK3 (32D7) Rabbit mAb (Cell Signaling Technology); 1:200 anti-phospho-Elk-1 (Ser-383), rabbit polyclonal IgG (Santa Cruz Biotechnology, Inc); 1:2000 anti-phospho-p44/42 MAPK (ERK1/2) (Thr202/Tyr204) (E10) mouse mAb (Cell Signaling Technology); 1:1000 anti p44/42 MAPK (ERK1/2) (137F5) rabbit mAb (Cell Signaling Technology); 1:2000 anti-phospho-SAPK/JNK (Thr183/Tyr185) (G9) mouse mAb (Cell Signaling Technology); 1:1000 anti-PARP (46D11) rabbit mAB (Cell Signaling Technology); 1:1000 anti-cleaved-PARP (D214) rabbit polyclonal Abs (Cell Signaling Technology); 1/2000 anti-Vinculin (E1E9V) XP rabbit mAb (Cell Signaling Technology) and 1:5000 anti-actin, clone 4 mouse mAb (Millipore). Either anti-rabbit (Bio-Rad) or anti-mouse (Cell Signaling Technology) horseradish peroxidase-conjugated secondary antibodies and Western Bright ECL Western Blotting Reagents (Advansta) were used to develop the blots. All experiments were reproduced in independent experiments. All experiments were performed two times.

**Incucyte proliferation assay** – 2000 A375 cells were seeded in each well of 96 well plate. Cells were incubated for 24 hours to adhere then treated with different doses of each inhibitor and incubated and analyzed using Incucyte ZOOM microscope (image recorder every 1 hour with a

10X objective). The real time growth confluence was estimated plotted using GraphPad Prism software.

**IncuCyte Apoptosis assay** - 2000 A375 cells were seeded in each well of 96 well plate. Cells were incubated for 24 hours to adhere then treated with different doses of each inhibitor plus constant concentration of the IncuCyte Caspase-3/7 reagent ) following the manufacturer protocol. Cells were incubated and imaged in the IncuCyte® ZOOM equipment with a  $\times 10$  objective at indicated time points. Number of apoptotic cells was normalized to the percentage area coverage (confluency) at the final time point to account for cell proliferation.

### 4.3. Computational Methodology

The crystal structure of ERK2 receptor complexed with *N*-[(1*S*)-1-(3-chloro-4-fluorophenyl)-2-hydroxyethyl]-2-(tetrahydro-2*H*-pyran-4-ylamino)-5,8-dihydropyrido[3,4-*d*]pyrimidine-7(6*H*)-carboxamide (2SH) (PDB code: 4OE6 [41]) was taken as the template for all docking calculations. Modeller software [52] was used to construct and refine the missing residues (177-187,202-204 and 331-333). The protonation state of the protein was predicted using H++ server [53]. All molecular docking calculations were carried out using Autodock4.2 software [54]. The pdbqt file for ERK2 was prepared according to the AutoDock protocol [55]. All docking parameters were kept to their default values. However, the number of GA runs was set to 250 and the maximum number of energy evaluation was set to 25,000,000. The docking grid was selected to encompass the ATP-active site of ERK2 receptor with a grid size of  $70 \text{ \AA} \times 70 \text{ \AA} \times 70 \text{ \AA}$  and a spacing value of  $0.375 \text{ \AA}$ . The atomic charges of inhibitors were calculated by gasteiger method [56]. The grid center was placed at 16.20, 7.50, 12.40 (XYZ coordinates). Prior to molecular docking, the 3D structures of the studied compounds were energetically minimized using MMFF94S force field with the help of SZYBKI software [57].

#### 4.4. Crystal Structure Determinations

The single-crystal X-ray diffraction study were carried out on a Bruker D8 Venture diffractometer with Photon100 detector at 123(2) K using Cu-K $\alpha$  radiation ( $\lambda = 1.54178$  Å for **3c**, **3f**) and Mo-K $\alpha$  radiation ( $\lambda = 0.71073$  Å for **6**). Direct Methods for **3c**, **3f** (SHELXS-97)[58] and dual space methods for **6** (SHELXT)[59] were used for structure solution and refinement was carried out using SHELXL-2014 (full-matrix least-squares on  $F^2$ ).[58] Hydrogen atoms were localized by difference electron density determination and refined using a riding model (H(N, O) free). Semi-empirical absorption corrections were applied.

**3c**: yellow crystals,  $C_{19}H_8BrNO_4 \cdot C_2H_6OS$ ,  $M_r = 472.30$ , crystal size  $0.18 \times 0.12 \times 0.03$  mm, triclinic, space group  $P-1$  (No. 2),  $a = 7.3950(2)$  Å,  $b = 10.0211(3)$  Å,  $c = 13.8015(4)$  Å,  $\alpha = 70.268(1)^\circ$ ,  $\beta = 78.915(1)^\circ$ ,  $\gamma = 79.360(1)^\circ$ ,  $V = 936.79(5)$  Å<sup>3</sup>,  $Z = 2$ ,  $\rho = 1.674$  Mg/m<sup>3</sup>,  $\mu(\text{Cu-K}\alpha) = 4.347$  mm<sup>-1</sup>,  $F(000) = 476$ ,  $2\theta_{\text{max}} = 144.2^\circ$ , 14049 reflections, of which 3661 were independent ( $R_{\text{int}} = 0.032$ ), 267 parameters, 1 restraint,  $R_1 = 0.026$  (for 3325  $I > 2\sigma(I)$ ),  $wR_2 = 0.065$  (all data),  $S = 1.05$ , largest diff. peak / hole =  $0.352 / -0.359$  e Å<sup>-3</sup>.

**3f**: yellow crystals,  $C_{21}H_{13}NO_4$ ,  $M_r = 343.32$ , crystal size  $0.26 \times 0.06 \times 0.04$  mm, monoclinic, space group  $P2_1/c$  (No. 14),  $a = 8.0265(3)$  Å,  $b = 12.3658(5)$  Å,  $c = 15.3573(6)$  Å,  $\beta = 93.529(2)^\circ$ ,  $V = 1521.38(10)$  Å<sup>3</sup>,  $Z = 4$ ,  $\rho = 1.499$  Mg/m<sup>3</sup>,  $\mu(\text{Cu-K}\alpha) = 0.864$  mm<sup>-1</sup>,  $F(000) = 712$ ,  $2\theta_{\text{max}} = 144.2^\circ$ , 15270 reflections, of which 2991 were independent ( $R_{\text{int}} = 0.024$ ), 235 parameters,  $R_1 = 0.034$  (for 2800  $I > 2\sigma(I)$ ),  $wR_2 = 0.091$  (all data),  $S = 1.06$ , largest diff. peak / hole =  $0.229 / -0.249$  e Å<sup>-3</sup>.

**6**: orange crystals,  $C_{28}H_{14}ClNO_6 \cdot \frac{1}{2} (C_3H_7NO)$ ,  $M_r = 532.40$ , crystal size  $0.40 \times 0.30 \times 0.20$  mm, triclinic, space group  $P-1$  (No. 2),  $a = 10.8841(4)$  Å,  $b = 12.3025(5)$  Å,  $c = 19.4831(8)$

Å,  $\alpha = 108.007(1)^\circ$ ,  $\beta = 104.210(1)^\circ$ ,  $\gamma = 92.144(1)^\circ$ ,  $V = 2386.89(16) \text{ Å}^3$ ,  $Z = 4$ ,  $\rho = 1.482 \text{ Mg/m}^{-3}$ ,  $\mu(\text{Mo-K}\alpha) = 0.213 \text{ mm}^{-1}$ ,  $F(000) = 1096$ ,  $2\theta_{\text{max}} = 55.0^\circ$ , 48590 reflections, of which 10949 were independent ( $R_{\text{int}} = 0.027$ ), 702 parameters, 2 restraints,  $R_1 = 0.043$  (for 9320  $I > 2\sigma(I)$ ),  $wR_2 = 0.117$  (all data),  $S = 1.04$ , largest diff. peak / hole =  $0.875 / -0.459 \text{ e Å}^{-3}$  (in the solvent dmf).

CCDC 1542037 (**3c**), CCDC 1539309 (**3f**), and 1539310 (**6**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via [www.ccdc.cam.ac.uk/data\\_request/cif](http://www.ccdc.cam.ac.uk/data_request/cif).

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